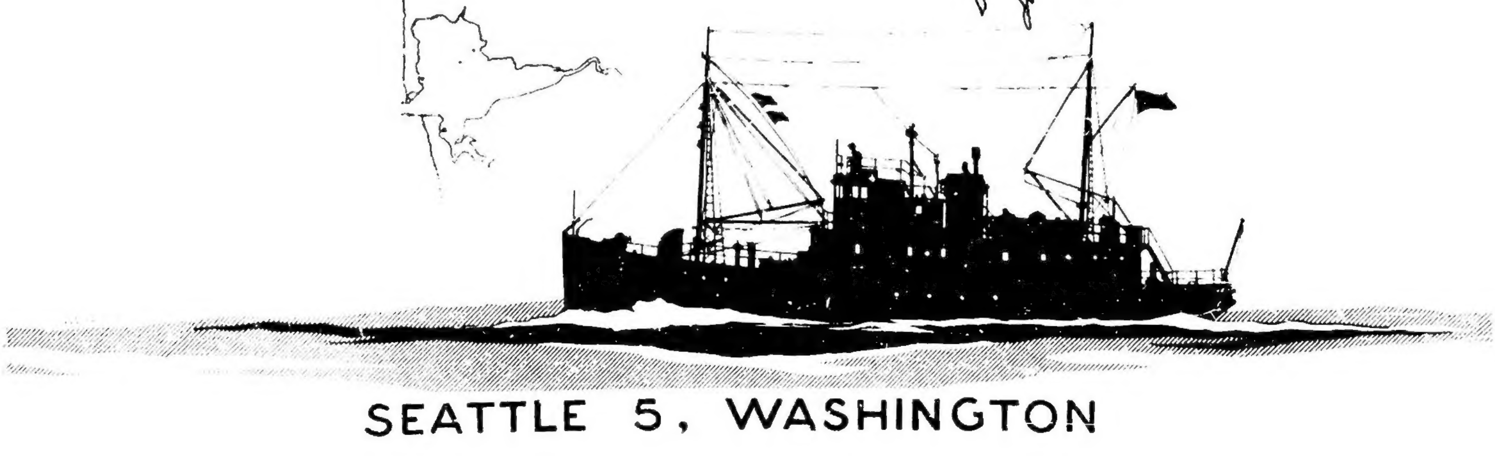
DEPARTMENT OF OCEANOGRAPHY
UNIVERSITY OF WASHINGTON

Technical Report No. 15

STUDIES ON LAKE WASHINGTON SHIP CANAL

Office of Naval Research
Contract N8onr-520 III
Project NR 083 012

Reference 53-5
December 1953



SEATTLE 5, WASHINGTON

UNIVERSITY OF WASHINGTON DEPARTMENT OF OCEANOGRAPHY
(Formerly Oceanographic Laboratories)
Seattle, Washington

STUDIES ON LAKE WASHINGTON SHIP CANAL

by

Gunter R. Seckel and Maurice Rattray, Jr.

Technical Report No. 15

Office of Naval Research
Contract N8onr-520/III
Project NR 083 012

Reference 53-5
December 1953

Richard H. Fleming
Executive Officer

ACKNOWLEDGMENT

The authors wish to express their sincere appreciation to the staff of the Department of Oceanography for their aid, suggestions and criticisms during the course of the investigation, and, in particular, to Dr. C. A. Barnes who initiated the investigations and Drs. R. H. Fleming and T. G Thompson for their interest and encouragement. Thanks are due to Mr. Eugene Collias and his technicians who collected and processed much of the data.

The authors also wish to express their thanks for the cooperation received from Mr. Fred Seidell, engineer in charge of the Ballard Locks, to the Naval Electronics Laboratory, San Diego, California, for the loan of the C-T-D recorder, and to the Office of Naval Research which made the investigation possible.

ABSTRACT

Salt water enters the fresh-water system of Lake Washington, Montlake Canal, Lake Union, Fremont Canal, and Salmon Bay through the U. S. Government Locks at Ballard. In each lockage operation the amount of saline water introduced is roughly twice the amount of water necessary to raise the water level in the locks. In order to take care of this inflow, a basin 600 m. long and 75 m. wide was dredged out to 3.7 m. below the upper miter sill. From the lower end of this basin, a siphon 2.7 $m.^2$ in cross section extends to the downstream side of the spillway, discharging an estimated 2.8 to 4.2 $m.^3$/sec. from the basin. However, the salt-water siphon and the Salmon Bay basin are inadequate on the basis of volume capacity, and also because the salt water flowing lakeward out of the locks travels essentially as a jet and spills over into Lake Union where it is no longer available to the siphon's flushing action.

During the summer when runoff through the canal system is at a minimum, the interface in Lake Union rises above sill level and salt water flows into Lake Washington. With large runoff during winter and spring, flushing of Lake Union takes place corresponding to the rates of flow. A discharge of more than 100 $m.^3$/sec. for 13 days was sufficient to flush the lake completely, while one of 50 $m.^3$/sec. prevented a rise of the interface in Lake Union.

Winter cooling in Lake Washington reduces its stability sufficiently so that wind mixing becomes an important factor in the prevention

of permanent salt-water stratification. The critical chlorinity necessary to prevent overturn is not known, but it is believed that it was almost reached in 1952. Approximately 25 per cent of the salt in the lake is flushed out annually by vertical mixing during the winter months.

In Montlake Canal where salt intrusion into Lake Washington occurs, 1 to 2 m.^{3}/sec. pass from the salt water into the surface water and are carried seaward. In Fremont Canal this rate would be somewhat larger, due to the velocity of the salt-water slug. The minimum fresh-water discharges necessary to prevent salt intrusion through Fremont and Montlake Canals are approximately 50 m.^{3}/sec. and 9 m.^{3}/sec., respectively.

Application of Keulegan's model studies on the mixing of stratified flows to both Lake Union and Montlake Canal shows that the criterion of mixing and the law of mixing rate hold for larger systems.

- - - - - - - - - - - -

In addition to the data presented in Appendices A, B and C of this report, there are additional data for observations made in this canal system. These are on file at the University of Washington and are available for inspection by interested parties.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

1.1 DESCRIPTION OF AREA

Lake Washington Ship Canal is located in Seattle, Washington, and connects the sea-water body, Puget Sound, with the fresh-water body, Lake Washington, as shown in Figure 1. The locks form the western entrance to the canal system (Figure 2), which, in order from west to east, consists of Salmon Bay, Fremont Canal, Lake Union, Montlake Canal, and finally terminates in Lake Washington.

The relative depths of these various sections are shown in Figure 3. The navigation channel is dredged and maintained everywhere at a minimum depth of 9 m. The bottom of Salmon Bay at the locks is approximately 15 m. below the lake surface. Lake Union is approximately 14 m. to 15 m. deep throughout its basin, and Lake Washington has a maximum depth of 65 m., which is reached within a short distance of the canal entrance. Both Fremont and Montlake Canals are straight cuts with cemented bulkheads and have a depth varying from 9.5 m. to 11 m.

The total water surface area is 95 $km.^2$ Drainage is from 440 $km.^2$ and mainly dependent upon precipitation throughout the year. It does not depend upon glacial streams and only to a minor extent on snow fields.

The Puget Sound region has a mild climate, with a rainy winter and a dry summer season. The mean temperatures for Seattle in January and July are 4.2° C. and 17.3° C., respectively. The mean monthly

precipitation for November, December and January is in excess of 12 cm., and in July and August is below 2.5 cm. (Climate and Man, 1941).

1.2 HISTORY

Before the canal system and the U. S. Government Locks (Ballard Locks) of the Lake Washington Ship Canal were completed and opened to traffic in August 1916, Lake Washington and Lake Union were separate lakes. The elevation of Lake Washington was between 9 and 10 m. above mean lower low water of Puget Sound. It drained from its south end through the Black and Duwamish Rivers, discharging into the southern portion of Elliott Bay. Lake Union was regulated at 6.4 m. above mean lower low water of Puget Sound by means of spillway gates at its extreme westerly end. The present Salmon Bay was part of Shilshole Bay; both were navigable only at high tide and were practically dry at low tide.

In construction of the canal system, the following changes were made: (1) the Cedar River was diverted to discharge into Lake Washington and thus became its main tributary; (2) a canal was cut between Lake Washington and Lake Union. The construction of the locks and spillway was such that the lake level could be controlled at 6.4 ± 0.3 m. (21 ± 1 feet) above mean lower low water. Thus, Salmon Bay was raised and Lake Washington was lowered so that the original Black River outlet ceased to exist.

The connection of the fresh-water lakes to Puget Sound by means of locks creates the problem of salt-water contamination of the fresh-water lakes. Each time the water level in the locks is raised from sea to lake level, the fresh water which is introduced at depth mixes with

the sea water which is at the bottom of the locks. When the upper gates are then opened, the diluted sea water flows upstream along the bottom of the canal, being replaced by fresh water.

In order to take care of the inflowing sea water, a basin 600 m. long and 75 m. wide was dredged out to 3.7 m. (12 feet) below the upper miter sill. From the lower end of this basin a siphon 2.7 $m.^2$ in cross section extends to the downstream side of the spillway, discharging an estimated 2.8 to 4.2 $m.^3$/sec. from the basin.

The siphon, however, is insufficient to remove all the salt water that enters the system through the locks, and some of it flows back into the deeper basin of Lake Union. This occurs especially during periods of light runoff or heavy lockage operations, which unfortunately coincide with the summer months. Lake Union thus acts as a secondary sump and tends to prevent or reduce the flow of sea water into Lake Washington, where it would accumulate and eventually stagnate as it does in Lake Union.

Original studies on salt intrusion into the lake system were made by T. G. Thompson. These were discussed by Smith and Thompson (1927). Beginning in October 1950, under the sponsorship of the Office of Naval Research, water samples were taken every 2 or 3 weeks in Lake Washington at Station 18 (depth 63 m.), at the two deep parts of Lake Union, Stations 10 and 8.5 (depths 15 m.), and Station 2 in Salmon Bay (8 m.), as shown in Figure 2.

1.3 PURPOSE OF THE INVESTIGATION

In order to enable a coastal engineer to prevent contamination of fresh-water bodies by sea water in systems such as the Lake Washington Ship Canal, it is important for him to understand the processes of salt intrusion and flushing. The purpose of the study, therefore, is first to clarify the processes involved, based on the survey data taken since 1950, and thus provide a basis for more detailed investigations; secondly, it is to gain insight into the mechanism of two-layered flow and mixing.

1.4 FIELD WORK

The survey data which were collected during the past 3 years are included in the appendices. They were collected with standard oceanographic apparatus, such as reversing thermometers and Nansen bottles. The shortcomings of this method of collecting in waters where there are chlorinity gradients of 2 $^{o}/oo$ (parts per thousand) per meter are first, the Nansen bottle is approximately 60 cm. long, and secondly, the difficulty of placing a sampling bottle exactly at a certain depth.

To obtain a chlorinity and temperature profile of the canal system in 1952 and to determine the continuous chlorinity variation in Fremont Canal in 1953, a C-T-D (Conductivity, Temperature and Depth) recorder was used. This instrument, which records the conductivity, temperature and depth, is still in development stage but shows promise of great usefulness in waters of low salt concentration. It is capable of considerable accuracy, but a nomograph must be used to obtain the chlorinity from the conductivity and temperature.

Current measurements were also made during the autumn of 1952 in Montlake Canal and again in July 1953 in Fremont Canal. On both occasions the Ekman current meter was used, its disadvantage being that it was too slow, considering the rapid fluctuations in current, to provide a nearly instantaneous current profile from top to bottom.

In the autumn of 1952, a remote-indicating propellor-type current meter, designed in the Department of Oceanography, was used to supplant the Ekman meter. This meter was sensitive to velocities less than 0.05 knot. Each revolution of the wheel operates a magnetic switch, thus transmitting electrical impulses which are counted by means of earphones. Unfortunately, the directional element was not completed at the time of use. The main advantage of the meter is the speed at which currents can be measured, since it does not have to be hauled aboard after every determination. Another advantage is its indication of reliability of the measurements from the regularity of clicks. Erratic clicks would mean weak and variable currents or some other interference.

In the determination of chlorinity and oxygen, standard methods of analysis were used. The former was determined by the Volhard method and the latter by the Winkler method.

The applicability of relations between chlorinity, salinity and density, given by Knudsen (1901) for sea water, has not been checked for the diluted sea water in the local lake system. The salinity and density, therefore, have not been included in the data. The relations given in Knudsen's tables were, however, used whenever the calculation of density was necessary. It was assumed that the chloride found in the system

was primarily due to sea-water intrusion, since the local fresh waters have a very low chloride content. Relative densities as computed should therefore be essentially correct, although subject to some error in actual numerical value.

1.5 INTERPRETATION OF RESULTS

In the analysis of the survey data, only those portions were used which would throw more light on the problem of salt-water intrusion and flushing in the lake system. For example, no attempt has been made to compute the heat budget of Lake Washington, although the annual temperature variations of the lake for a period of 3 years are available. In other words, the following sections should not be looked upon as a complete study of the system but principally as a guide to more detailed and complete investigations of the various phases discussed.

The study of the canal system is divided into four sections which are: Ballard Locks to Lake Union, Lake Union, Montlake Canal, and Lake Washington. A summary of the over-all picture will be found in the conclusions.

2. SALT WATER INTRUSION THROUGH THE LOCKS, SALMON BAY AND FREMONT CANAL

2.1 INTRODUCTION

The geometry of the locks and the mechanism of lockage operations are discussed in this section. The volume budget in relation to the Salmon Bay basin and the salt-water siphon is determined. Model studies of O'Brien and Cherno (1934) are applied to the Ballard Locks, and

continuous chlorinity data and current measurements taken in the Fremont Canal 16 July 1953 are analyzed.

2.2 THE LOCKS AND LOCKAGE OPERATIONS

For the purposes of this section, only those dimensions of the locks are discussed which aid in the analysis of lockage operations. A more detailed description is to be found in Appendix A-1.

Figure 4 shows diagrammatically the vertical dimensions of various parts of the large locks and their relation to the lake and the various sea levels. Taking the mean lake level of 6.4 m. above mean lower low water of Puget Sound as the datum, then the upper miter sills of the large lock and the small lock are 11.3 and 5.2 m. below this datum, respectively. The intake culvert for the large lock is 4.3 m. high and at a depth of 8.5 to 12.8 m. below the datum; that for the small lock is 1.1 m. high and 4.1 to 5.2 m. below the surface. These culverts fill the locks through laterals at the bottom of the chamber.

The mechanism of operation for the large lock can now be described. After the lower gates are opened to Puget Sound, any mixture of fresh and sea water is rapidly replaced by Puget Sound water (Smith and Thompson, 1927). The water in the locks, therefore, just prior to raising the level is always sea water. In raising the water in the locks from sea to lake level, lake water is introduced into the locks through culverts at the bottom of the chamber and actually "bubbles" through the sea water. The resulting mixing is not complete, but the water introduced from Salmon Bay will become more saline and the sea water will be diluted. After the lock level is raised to that of the

lake, the upper gates are opened to the canal side. The impounded water, being denser than that at the same level on the lake side, will rapidly flow toward the lake and be replaced by lighter surface water (Smith and Thompson, 1927).

As mentioned above, the intake culvert of the large lock extends from 8.5 to 12.8 m. below the lake surface datum. Chlorinity data indicate that during the summer months diluted sea water (referred to as salt water in the following sections) is to be found at these depths. Salt water is therefore used to fill the large lock rather than lake surface water (referred to as fresh water in the following sections).

The sequence of flows to be noticed in Salmon Bay and Fremont Canal are, therefore: (1) a northwesterly (seaward) set or a marked reduction of southeasterly (landward) set in the bottom salt layers when the large lock is being filled; (2) a strong seaward current in probably all waters of the canal after the upper lock gates are opened; (3) a salt-water surge landward, following the strong seaward current, in the bottom layers of Salmon Bay and the canal.

The sequence of events in the small lock is similar except for the initial flow. The intake culverts are located at a level where fresh water is generally to be found, and the deeper, more saline water of Salmon Bay does not flow seaward into the lock.

The analysis of lockage operations shows that the water used in filling the large lock is salt water which flowed out of the lock into Salmon Bay in previous lockages. When large lockages follow rapidly, one upon another, or when the siphon is not functioning, the salt water in the basin above the locks will become more concentrated. A high

chlorinity of 7 to 8 ‰ at the bottom of Lake Union, instead of the normal 5 to 6 ‰ as in 1951, was noted in the autumn of 1952 when the siphon was partially closed.

2.3 THE VOLUME BUDGET

With an understanding of the locking process and a knowledge of the sill and culvert depths, the maximum and minimum amounts of sea water which would flow back into the canal system after the upper lock gates are opened can be determined.

Assuming that the culverts of the large locks will withdraw water, primarily from a depth below 8.5 m., which will "bubble" through sea water in the locks of approximately the same temperature as that of the lake water, then all the water in the locks will be more dense than the water to be found above 8.5 m. in Salmon Bay. Upon opening the gates, 8.5 x (surface area of the large lock) $m.^3$ will flow back into the lake system. This volume is the minimum amount. The maximum amount that could flow out, and probably does when Salmon Bay is well flushed of salt water, is the amount of water contained in the locks above the upper miter sill. The volumes involved are given in Table 1 below.

These figures illustrate some important points. First, the amount of fresh water used in lockage operations is much larger than that used in raising the level of the large lock. It is the amount of water used to displace the salt water flowing into Salmon Bay which is approximately twice the amount used in raising the level of the lock. Secondly, the amount of fresh water used is independent of the tide level. Thirdly, the computed volumes of salt-water intrusion show that

the siphon and the Salmon Bay basin are not adequate to prevent lake contamination.

TABLE 1

LOCKS		SURFACE AREA OF LOCK m.^{2}	SALT WATER RELEASED INTO SALMON BAY				NET VOLUME USED IN LOCKAGES FOR MEAN SEA LEVEL[b] m.^{3}
			DEPTH[a] OF CULVERT m.	MINIMUM VOLUME m.^{3}	DEPTH OF UPPER SILL m.	MAXIMUM VOLUME m.^{3}	
Large Lock	F[c]	6150	8.5	52,000	11.3	69,000	27,000
	U	3350	8.5	29,000	11.3	34,000	15,000
	L	2800	8.5	24,000	11.3	31,000	12,000
Small Lock		420	4.1	1,700	5.2	2,200	1,800

[a] Depths are referred to lake datum 6.4 m. above m.l.l.w.
[b] Mean sea level is 2 m. above m.l.l.w.
[c] By means of an additional lock gate, either the full (F), the upper (U), or the lower (L) chamber can be used for lockages.

The salt-water siphon has a capacity of approximately 3.5 m.^{3}/sec. or 12,600 m.^{3} per hour. This rate of flow is quite adequate to take care of the 2200 m.^{3} of salt water per small lockage; however, the minimum amount of salt water intruding into the system from a large lockage, using only the lower chamber, is twice the hourly siphon capacity.

Computing the water budget on a daily basis, one finds the average amount of water used for lockages during the summer months to be 425,000 m.^{3} per day, and the siphon capacity to be 302,000 m.^{3} per day. There is, therefore, an excess of 123,000 m.^{3} of salt water

entering the canal system per day, an amount so large that the adequacy of the Salmon Bay storage capacity must be considered. This is approximately 425,000 $m.^3$ below the depth of 9 m. Thus, with the siphon in full operation it would only take 4 to 5 days to fill the basin; with the siphon closed it would take only 1 day, with the additional effect of filling the basin with more concentrated salt water.

2.4 MODEL STUDIES APPLIED TO THE BALLARD LOCKS

The considerations of the previous section were based on the conservation of fresh and salt water with no consideration given to dynamics. In the following paragraphs the results of model experiments by O'Brien and Cherno (1934) are applied to the Ballard Locks.

Their problem was the study of salt-water intrusion into fresh-water systems through locks similar to those under consideration in this chapter. O'Brien and Cherno found that, upon opening the lock gates, the salt water would slide under the fresh water and move along the bottom while the fresh water moved in the opposite direction near the surface. At some instant later, the salt water would continue to move along the channel as a slug of constantly diminishing height and increasing length.

The authors also derived an expression for the initial velocity, V_o, and determined the empirical relation between the percentage decrease of this velocity and the distance from the locks for various values of the model characteristic, K, a function of the lock length and depth and the difference in specific gravity. The equations for the initial velocity and the model characteristic are:

$$V_o = \pm \sqrt{\frac{g\,d\,s}{2\,(G_1 + G_2)}}\text{ , and}$$

$$K = \frac{L_o}{d^{2.5}\,s^{0.5}}$$

where g is the acceleration due to gravity; d is the depth of the channel; G_1 and G_2 are the specific gravity of the fresh and salt water, respectively; $s = G_2 - G_1$; and L_o is the length of the lock (which for the large lock is 252 m. and for the small lock 46 m.).

By applying the lock dimensions to the above formulae and to the empirical relations between L/L_o and V/V_o found by O'Brien and Cherno (V is the velocity of the slug at a distance L from the lock), one might at least be able to find the order of magnitude of the velocities involved. Assume that the salt water inside and the fresh water outside the locks is homogeneous, prior to the opening of the gates, and that the difference in specific gravity is 6×10^{-3}. The computed V_o for the large lock then is 41 cm./sec., which, from experience, seems to be of reasonable order of magnitude.

The other computed parameters, K and V/V_o, are shown in Table 2 below. The values for the velocity of the salt water slug are still large when reaching Lake Union and practically unchanged at the end of the Salmon Bay basin. One can therefore allow for considerable dissipation and still expect the salt water slug to reach Lake Union.

TABLE 2

LOCKS	K[a]	V/V_o			
		END OF SALMON BAY BASIN		LAKE UNION	
		L/L_o	V/V_o	L/L_o	V/V_o
Large Lock: Full Chamber	1.3	4.3	.97	12.7	.73
Half Chamber	.6	8.5	.9	25.	.6
Small Lock	1.6	23.	.6	70.	.3[b]

[a] In order to use the empirical relations given by O'Brien and Cherno, the dimensions of feet had to be used in the computation of K.

[b] Approximate value.

Dissipation can be expected to take place in Salmon Bay due to two reasons, neither of which are expected to be very serious--one is the widening of the channel and the other is the deepening of the basin. Charts indicate that outside the deeper, fairly straight dredged channel the water is considerably more shallow. The salt water would flow in this deeper channel, which does not deviate very much from the model channel other than in depth.

As was mentioned before, the model channel had the same depth as the lock. The channel in Salmon Bay, on the lake side of the Ballard Locks, however, drops 3.7 m. below the upper miter sill and then rises slowly toward Fremont Canal with approximately the same depth as the sill. The necessary energy for the salt water to overcome the gentle slope toward Fremont Canal would be derived, to a great measure, from the energy gained in dropping 3.7 m. from the sill level.

V/V_o for the salt-water slug from the small lock is only 30 per cent upon reaching Lake Union. V_o is approximately 22 cm./sec. if computed on the basis of a lock and channel depth of 5.2 m., but an estimated 50 cm./sec. if the additional gain of kinetic energy due to the drop of 5.5 m. from the upper miter sill to the channel bottom is taken into consideration. This would give the slug a velocity of approximately 15 cm./sec. upon reaching Lake Union.

Besides the model studies of O'Brien and Cherno, Fries and Viney (1933) made some model studies of the Lake Washington Ship Canal, in view of finding a solution to salt-water intrusion into the lake system. Their results substantiated the assumption that water is essentially traveling into Lake Union as a jet.

In addition to the model studies, there is evidence that salt water enters Lake Union as a jet, based on the survey data taken in the lake. After the complete flushing of Lake Union in February 1951 (section 3), the fresh-water flow remained greater than 49 $m.^3$/sec., an average velocity of approximately 10 cm./sec. in Fremont Canal. In spite of this flow and the fact that the Salmon Bay basin was completely flushed, salt water reappeared in Lake Union. One can conclude, therefore, that the mechanism by which salt water can reach the lake under these adverse circumstances is by a stream which has considerable momentum.

2.5 ANALYSIS OF FREMONT CANAL DATA

In the investigation of salt-water intrusion, it is important to know what part, if any, the canals play in controlling the flow.

For this reason, continuous chlorinity and current measurements were made in the Fremont Canal 16 July 1953.

Before anchoring in the canal, hydrographic stations were occupied in Lake Union (Station 8.5), under the Aurora Bridge (Station 5.7), at three stations in the Fremont Canal (Stations 5.5, 5.2 and 4.6), and at Station 2 in Salmon Bay. The locations of the stations are indicated in Figure 5. The instrument used in these measurements was the C-T-D recorder. In the afternoon, an anchor station was occupied at the mid-point of the canal (Station 5.2, Figure 5). The C-T-D was again used to take continuous chlorinity and temperature records, mainly at a depth of 8 m., where the conductivity variations were most pronounced. During the same period, current measurements were made using the Ekman current meter.

Since the conditions in the canal were expected to be quite variable, it was hoped that the measurements could be correlated with lockage operations. This proved to be difficult. The data are included, however, and an attempt at interpretation is made in the hope that it will help in future, more detailed examinations of the canal.

Figures 6a and 6b show the continuous chlorinity trace which was begun shortly after 1330 while at anchor. Isolated values for the chlorinity obtained before that time are also plotted, and a dashed line shows the possible variation. The continuous trace shows small variations with periods of 1 to 2 or 3 minutes superimposed on larger wave-like forms with periods of approximately 20 minutes. The maximum chlorinity amplitude is approximately 0.8 $^{o}/oo$ at 8 m. at 1335, and decreased to between 0.2 and 0.3 $^{o}/oo$ at about 1515.

Figure 7 shows the gross variation of chlorinity at Station 5.2 at various depths from 1030 until 1600. A T-Cl (Temperature-Chlorinity) curve (Figure 8) was also prepared to aid in the identification of the water in Fremont Canal as of either Lake Union or Salmon Bay origin. Table 3 below shows the time and net volumes used in lockage operations 16 July 1953. The current velocities obtained while at anchor are indicated schematically in Figures 6a and 6b.

TABLE 3*

LARGE LOCK			SMALL LOCK		
TIME 16 July 1953	NET VOLUME		TIME 16 July 1953	NET VOLUME	
	1000 $m.^3$	1000 $ft.^3$		1000 $m.^3$	1000 $ft.^3$
650	13.6	479	832	1.8	62
925	16.3	575	910	1.8	62
1130	17.6	623	935	1.8	62
1315	18.7	659	1010	1.8	62
1500	18.7	659	1045	1.8	64
1538	18.2	641	1105	1.9	67
			1135	2.0	71
			1200	2.0	71
			1230	2.1	73
			1250	2.2	76
			1330	2.2	78
			1400	2.2	78
			1420	2.2	78
			1450	2.2	78
			1515	2.2	76
			1540	2.1	73

* Lockage times and net volumes obtained from the Corps of Engineers, Ballard Locks, 16 July 1953.

It is almost impossible to correlate lockage operations with the chlorinity variations, due to lack of information of exact lockage times. The larger variations of 20-minute period are probably due to small lockage operations, which occurred approximately once every 20 or 30 minutes during the day. The continuous decrease of chlorinity amplitude (Figures 6a and 6b) during the afternoon could be due either to the action of the salt-water siphon or to the draining into Lake Union or both.

Current measurements taken during the afternoon made interpretation even more difficult. With the high chlorinity found at 8 m. at 1335, salt water might be expected to flow into Lake Union at and below that depth. Current measurements made throughout the anchor period showed, however, a seaward set at all depths except for the surface (Figures 6a and 6b). Here, due to a northwesterly wind, the set was toward Lake Union. A lakeward set occurred, probably for only a brief period, at 10 m. at 1440 and corresponds with a peak on the continuous chlorinity trace.

The T-Cl curves (Figure 8) show that the canal water below 7 m. was of the Salmon Bay type, except at 1535 when the low chlorinities were observed at 8 m. Even then the water found at 10 m. was of the Salmon Bay type. From this, also, one would therefore conclude that the water below 8 m. flowed toward Lake Union.

A clue to an explanation of this apparently anomalous behavior might be found in the distribution of direction-indicating beads of the Ekman meter when at 10 m. At the 1340 current determination, there were three beads indicating a seaward set and one bead a lakeward set. Again,

at 1440, two beads indicated lakeward flow and one bead seaward flow; in the former the velocity was 10 cm./sec. and in the latter 6 cm./sec. The duration of measurement in each case was 4 minutes, so that the start of the 1340 measuring period may have been at the end of the lakeward surge, with the following seaward set corresponding to the decrease in chlorinity at 8 m. The reverse may have occurred at 1440.

Not much more can be done with the current measurements other than to attempt to compute the volume flow. Two complete vertical profiles of current velocity were taken in the canal. The first took from 1255 to 1340, during which time there was one large and one small lockage; the second took from 1350 to 1440 with two small lockages. For the sake of the following approximations, it is assumed that a steady state existed during the period of measurement. This is not the case, but the findings may indicate the order of magnitude involved.

Considering the first profile, the relatively large flow of 33 cm./sec. at 6 m. occurred only 5 minutes after the large lockage. The net rate of flow through the canal at Station 5.2 (cross-sectional area 550 $m.^2$), based on this first current profile, is 46 $m.^3$/sec. Subtracting 3.5 $m.^3$/sec. used in the salt siphon leaves a net of 42.5 $m.^3$/sec. for filling the large lock. This required 19,000 $m.^3$ and could therefore be done by the computed rate of flow in about 7 minutes. The time actually required to fill the large lock is from 5 to 10 minutes, depending on the height of tide.

Similar computations for the second current profile gave a rate of flow of 22 $m.^3$/sec. and, after the amount for the salt-water siphon was subtracted, a net flow of 18.5 $m.^3$/sec. This would fill

the small lock, using 2200 m.^{3}, in approximately 2 minutes, which is a little less than the normal time required. In each case, the total computed flow was probably below the actual rate of flow because of the time involved in making the measurement.

Finally, rather large current velocities were observed at the 9 m. depth at 1517 and 1527. Together with the low chlorinities observed at this time, it seems as if a large volume of water was drawn out of the lake system. Within a period of 1 hour after 1450, there were actually two large and three small lockages.

The shortcomings of the observations are rather obvious. In systems with rapid velocity changes, it is important to have an instrument which can be operated considerably faster than the Ekman meter, without loss of the directional element, and preferably a recording type. The chlorinity was determined continuously at one level because the significance of the variations was not known until the C-T-D trace was interpreted.

Assuming that a salt-water slug from the large lock is at least twice as long as the lock and travels at 30 cm./sec., then it would take 15 to 30 minutes to pass any one place. Therefore, taking vertical profiles every 5 minutes would provide more information about the changes throughout the depth of the canal, besides giving sufficient data for correlation purposes with lockage operations.

Another shortcoming in this instance is the time of lockage operations. The time appearing on the lock master's log can be any time between the closing of one gate and the opening of the other, a period up to one-half hour. In other words, the filling time of

the lock and the opening of the upper gates are the important times to record.

On the positive side, one can say that the previous discussion describing the sequence of flows due to lockage operations was not disproved. It must again be emphasized that when the large lock is being filled, water is drawn from the lower, salty layers of Salmon Bay. This will tend to reduce or reverse any salt flow into Lake Union, and was observed in the variability of velocity in the lower 2 m. of the canal.

It should be possible to detect the large seaward surface flow of fresh water only a short time after the opening of the upper gates. Considering the disturbance to be similar to a solitary wave in shallow water, then it should be noted in Fremont Canal within 6 minutes, assuming the depth to be 10 m. and the distance to be 3.5 km. The assumption is supported by the high fresh-water velocity at 1320, only 5 minutes after a large lockage; and, again, by the low chlorinities only a short time after a small lockage at 1515 and a large lockage at 1530.

A salt-water surge, on the other hand, was not observed directly, but must have occurred in order to explain the high chlorinities in the canal earlier in the afternoon. Based on the computations of the previous section, it would take 2 to 3 hours for the salt water to travel the 3.5 km. to the canal. Thus, the salt water from the 1315 lockage could not have arrived by the time the observations were discontinued, and then was probably delayed by the high westerly flow after 1515. It is unfortunate that observations had to be discontinued before the arrival of the salt water from the 1500 and 1530 lockage operations.

3. FLUSHING OF LAKE UNION

3.1 INTRODUCTION

Lake Union has an area of 3.7 $km.^2$ and is aligned in a north-south direction, branching into two arms at the north end (Figure 9). One branch is oriented in a northeasterly direction through which the fresh water enters from Lake Washington; the other branch is oriented in a northwesterly direction and joins with the Fremont Canal. The lake has two deep portions of 14 to 15 m., one in the southern and one in the northern section, separated by a sill approximately 12 m. deep.

In the survey operations, two stations were generally occupied in the lake: Station 10 in the northern section and Station 8.5 in the southern section, as indicated in Figure 9.

This section will be principally concerned with the analysis of the chlorinity variations at Station 10 in relation to the fresh-water flow through the canal system. Thus, the discussion will begin with the chlorinity and total flow variations at Station 10, to be followed by a qualitative interpretation. Model studies by Keulegan (1949) will be considered next and applied to the lake, followed by general considerations of the criterion of mixing as applied to the lake conditions. Finally, it will be shown that sloping isochlors between Stations 10 and 8.5 can be correlated with salt intrusion or flushing of the lake. No correlation has been found between interface slope and wind, for which more precise measurements would be necessary.

The term interface, used frequently in this section, is defined as the surface which separates the distinct surface lake water in which

the chlorinity gradient is of the order of hundredths of one part per thousand per meter or less from the lower layers in which the chlorinity gradient is usually at least ten times that of the surface water. The 0.5 $^{o}/oo$ isochlor is generally found so close to the interface that for the practical purposes of this section they will be used interchangeably.

3.2 VARIATION OF CHLORINITY AND FRESH-WATER FLOW IN LAKE UNION 1951--1953

It is evident that Lake Union performs the important function of "catch basin" for salt water that is not impounded in Salmon Bay or returned to the sea by the salt-water siphon. To illustrate the annual processes of salt intrusion and flushing, the isochlors of 0.5, 1, 2, 5 and 7 $^{o}/oo$ at Station 10 were plotted in Figures 10a, 10b and 10c, starting January 1951 and continuing until October 1953, together with the net rate of discharge through the canal system as obtained from the engineers at the locks.

The rate of discharge plotted is that averaged over a 5-day period and represents the water used in lockages, the siphon, the fish ladder, leakage, and water wasted over the spillways and through the culverts of the large lock. The rate of flow through the siphon is approximately 3.5 m.^{3}/sec., that used in the fish ladder is 0.4 m.^{3}/sec., and the amount leaking through the locks and valves is approximately 0.6 m.^{3}/sec. This gives a continuous rate of flow through the lock system of approximately 4.5 m.^{3}/sec., in addition to which must be added the amounts used in lockages and that wasted over the spillways and through the culverts. This volume is the same as that flowing through the lake and, therefore, must be considered in the flushing action.

Engineers are somewhat uncertain about both the exact amount of water flowing through the siphon and the leakage. The error, however, is negligible when compared to a flow of 33 $m.^3$/sec. or more, as is the case during the winter and spring months. When Figures 10a, 10b and 10c were prepared, the exact amount of water used in lockage operations for 1953 had not yet been computed. In the preparation of the total flow curve, therefore, the average monthly amounts for lockages of the previous year were used. This again would introduce only a small error during the winter and spring months. The approximate nature of the curve is indicated by a dashed line after July when no more water was wasted through the spillways and culverts.

The dashed line of the chlorinity profiles shown in Figures 10a, 10b and 10c indicate the approximate depth at and below which dissolved oxygen was absent and hydrogen sulfide generally present.

Starting with 10 January 1951 (Figure 10a), the 0.5 $^{0}/_{00}$ isochlor was at 12.5 m.; subsequently, it rose to 11 m. and then dipped to disappear completely during the middle of February 1951. During this period the isochlors were rather closely spaced, and stagnant water was present in the lower layers. This likewise disappeared in February.

The total flow curve also showed some variation during January and reached a peak during February, when a flow of more than 100 $m.^3$/sec. lasted for 13 days. The highest 5-day average flow during this time was 290 $m.^3$/sec., with the peak flood of 300 $m.^3$/sec. on 13 February.

Soon after the flushing of the lake, salt water began to reappear more or less in steps. These steps of sharp increases in chlorinity seemed to coincide with decreases in flow, which remained

generally above 49 $m.^3$/sec. for the first 25 days of March. After March, as the runoff through the system decreased, the amount of salt increased rapidly, particularly in concentrations between 1 and 2 $^o/oo$. Dissolved oxygen also decreased rapidly, and at the end of April hydrogen sulfide began to reappear.

After 16 June no more water was wasted either over the spillway or through the culverts, and salt water of higher chlorinity appeared as a steady increase of chlorinity in the lake throughout the summer and early autumn. At the same time the amount of stagnant water increased at approximately the same rate.

With the beginning of October the rain season returns to the region, and, depending on the lake level, engineers at the locks begin to waste water. This occurred toward the end of 1951, and as soon as the flow had increased to approximately 33 $m.^3$/sec. 14 November, the 5 $^o/oo$ isochlor dropped sharply to 14 m., but by 29 November it was back at 11 m.

This general pattern of flushing during the winter months and increase of salt content during the summer was repeated in 1952 and 1953, with the exception of the complete flushing experienced in February 1951. During the winter and spring of 1952 precipitation was below average, and, as can be seen in Figure 10b, wastage of water was well distributed throughout the first 6 months of the year with amounts considerably below 50 $m.^3$/sec. most of the time. Discharge only once exceeded this for a brief period of 16 days in February. This was reflected in a dip of the isochlors which, however, rose again shortly thereafter, corresponding to a rather low runoff for that period.

During April and May there were three brief periods of flow greater than 40 $m.^3$/sec., which were reflected in a lowering of the interface by approximately 1 m.

After the middle of May 1952 the isochlors began to rise steadily. From July through the rest of the year the water flowing through the system was just that used in lockage operations, fish ladder, and siphon. In the chlorinity profile the 5 °/oo isochlor appeared at the end of August, as in 1951. Subsequently, however, the chlorinity increased rapidly with the appearance of the 7 °/oo isochlor below 10 m.

Noteworthy is the sudden drop of the 0.5 °/oo isochlor after 12 November 1952, which continued throughout December although there was no wastage of water during that period. On 7 January 1953 the engineers began to waste water. Notwithstanding a flow greater than 80 $m.^3$/sec. for 30 days, the interface level did not drop below 10 m. until March. The 7 °/oo isochlor level dropped very slowly during the first 3 months of 1953 until it disappeared in May. The 0.5, 1, and 2 °/oo isochlors began to rise during May as they did in previous years; however, the 5 °/oo isochlor continued to decline.

Generally it can be stated that the peak runoff takes place in January and February which are months of high precipitation in the region. Also, during the winter and early spring the chlorinity gradient below the interface is greater than during the summer and autumn. Flushing appears to be more effective when the chlorinity, and therefore the density, gradient is relatively small (November 1951) than in winter when it is larger (January and February 1952 and 1953).

Before proceeding with a discussion of the flushing processes, it should be repeated that the runoff into the lake system is primarily rain-fed. In addition to above-normal precipitation during January, in the 5 days prior to 12 February 1951 Seattle received approximately 11.5 cm. of rain, most of which fell on the 7th, 8th and 9th. In order to keep the level of the lake within its limits, the water due to the excessive rainfall had to be wasted, resulting in the high rate of flow through the system in February 1951.

It should also be mentioned that during the dry summer of 1952 the lake level was rapidly approaching the lower limit of 6.1 m. above mean lower low water of Puget Sound. The engineers were faced with the possibility of not being able to operate the locks and on 5 September decided to close the salt-water siphon. It remained closed until 19 September, when it was partially opened until 5 December.

3.3 QUALITATIVE INTERPRETATION

Qualitatively, one can say that Lake Union will be flushed completely when the discharge through the system is in excess of 100 $m.^3$/sec. for several days, as was the case in February 1951. Flushing to a certain extent takes place when the discharge is greater than 50 $m.^3$/sec. This, however, seems to depend not only upon the density difference between the upper and lower zones but also upon the density gradient below the interface. For example, in October 1951 the density gradient was considerably smaller than in the following winter and spring, and a rate of flow of 50 $m.^3$/sec. produced a greater dip in the interface than did 65 $m.^3$/sec. the following February. It can be assumed

that the water above sill level (10 m.) drained out when the flow increased, but flushing by the process of mixing extended to 4 m. below that depth.

The importance of density difference can be seen in the comparison of February 1952 with February 1953 in Figures 10b and 10c. In each case the interface was at approximately the same depth, but the chlorinity in the salt-water layer in 1953 was higher than in 1952. A flow of more than 82 m.^{3}/sec. in 1953 was not able to flush the lake any more than 65 m.^{3}/sec. in the previous year.

A flow of 30 m.^{3}/sec. to 50 m.^{3}/sec. seems to be able to do some flushing over a period of 2 to 3 months, as was the case in April and May 1952 and 1953 when the interface was lowered by approximately 1 m. However, this rate of flow does not prevent new salt water from flowing into the lake, as was the case during the spring of 1951 and apparently again during December 1951 and January 1952.

In addition to the observations above, three apparently anomalous phenomena can be observed in Figures 10a, 10b and 10c. The first is the rapid reappearance of salt water after the initial flushing of November 1951. Refilling Lake Union with salt water from 14 to 11 m. in 15 days seems rather rapid, especially in view of the high runoff. It is reasonable to assume, then, that the salt water drained from the southern part to the northern part of the lake where the flushing action actually takes place.

The presence of stagnant water between layers of water of normal oxygen content (0.55 mg-at/L) 14 November 1951 suggests that some new, colder salt water penetrated into the lake after the initial flushing.

The temperatures at 14 and 15 m. on this date were 12.34° and 12.72° C. and at 11 and 13 m. above 15.27° and 15.26° C., respectively. During the preceding October, temperatures were all above 15° C.

Data for 29 November suggest that this colder, new salt water was replaced by stagnant, warmer salt water (above 15° C.) which could only have come from the southern part of the lake. Subsequently, data during December and January indicate that the rising isochlors are also due to new and colder salt water, although the bottom 2 m. of the lake remained stagnant.

The second apparently anomalous phenomenon occurred when the interface level dropped rapidly in November 1952, although the flow through the system was only approximatelv 6 $m.^3$/sec. so that flushing due to mixing could not have taken place. Since the siphon in Salmon Bay was closed down, the only place salt water above 10 m. was able to flow was into Lake Washington. This was actually the case, as will be shown in sections 4 and 5. An explanation for the rather sudden drop of the interface must be found in lockage volumes. No large-scale change was found after 12 November. The average daily net amount of water used in large lockages, when salt water was still rising in Lake Union, was 229,000 $m.^3$; between 12 November and 24 November, during the drop of interface, the average daily amount was 200,000 $m.^3$ The lower average flow in the second 12-day period is mainly due to low lockage volumes on the 13th, 16th and 20th, which were 110,000 $m.^3$, 80,000 $m.^3$ and 160,000 $m.^3$, respectively. It is reasonable to assume that the drop in interface took place on these days when not only the

salt inflow was low but when, due to a reduced net flow, any possible control action of Montlake Canal was also reduced (section 4).

The third phenomenon to be discussed is the disappearance of the 7 ^{o}/oo isochlor in May 1953, although the interface level in Lake Union was rising at that time. It was shown in section 2 that the possible manner of salt intrusion into Lake Union is as a jet, with considerable momentum which would increase as the water flows down into the lake. It would, therefore, have sufficient energy to penetrate and mix with heavier water in the lake. Thus, if the entering water has a chlorinity of 2 to 5 ^{o}/oo and mixes to some extent with 7 ^{o}/oo water, one would expect the heavier water to become more diluted and finally the 7 ^{o}/oo isochlor to disappear. Figure 10c indicates that the salt water entering the lake had a chlorinity of 2 to 5 ^{o}/oo during July, August and September 1953, and that the amount of water of chlorinity greater than 5 ^{o}/oo was probably decreasing by a process of dilution described above.

3.4 MODEL STUDIES AND THEIR APPLICATION TO LAKE UNION

To put the flushing of Lake Union on a more quantitative basis, one might compare it to model results described by Keulegan (1949). He demonstrated that a light liquid flowing over a denser liquid generates internal waves. With an increased velocity these become sharp-crested, ejecting eddies from the denser liquid which are carried away by the upper liquid. It is shown that this is essentially the process of flushing taking place in Lake Union.

In the model experiments, U_o was defined as the maximum velocity at which no mixing took place and U_1 the velocity at which slight mixing took place. U_c, the mean velocity of U_o and U_1, was chosen to represent the critical velocity. On the basis of the experiments, a dimensionless constant was determined and called the criterion of mixing, ξ. It relates the important parameters of mixing in the form:

$$\xi = \frac{(\nu_2 \; g \; \Delta\rho/\rho_1)^{1/3}}{U_c}$$

where ν_2 is the kinematic viscosity of the denser liquid, g is the acceleration due to gravity, and $\Delta\rho$ is the density difference. The criterion was determined to be 0.178 for turbulent flow.

Before application, the model and Lake Union should be compared. First, the pool of heavy liquid was not in motion, which is essentially true also for the salt water in the lower stratum of the lake.

Secondly, mixing took place in a canal. It did not take place at the end of a channel which suddenly widens into a large basin, at the bottom of which there is a layer of heavy salt water (the picture of Lake Union when observed superficially). Fortunately, Lake Union is similar even in this respect to the model. Figure 11 shows the bottom profile of the northeast branch of the lake. It can be seen that in this channel which extends from the University Bridge to the main body of the lake the maximum depth is approached. The branch, therefore, forms part of the northern basin of the lake, and it is there where flushing action due to surface water flows can be expected.

Thirdly, both the light and heavy liquid in the model were homogeneous. This is true only for the surface water of the lake. The salt water shows various degrees of density gradients, as is evident from the chlorinity profile in Figures 10a, 10b and 10c, but resembles the model more closely in winter and spring when the salt gradient below the interface is large.

The only problem in the application of the criterion lies in the proper choice of the density of the heavy liquid. The model experiments showed that mixing is a process taking place at the interface. It is reasonable to assume that the lower stratum will be untouched, especially when the fresh-water flow is close to the critical mixing velocity.

With this difficulty in mind, Table 4 below has been prepared from actual data in Lake Union for various dates during the past 3 years. The table shows the following: the mean σ_{t1} for the surface water*; the mean σ_{t2} for the salt water; ν_2, the kinematic viscosity for the bottom water; $\Delta\rho$ (or $\Delta\sigma_t \times 10^{-3}$), the density difference computed from the above two values, σ_{t1} and σ_{t2}; and U_c, the critical velocity based on Keulegan's criterion of mixing, $\Phi = 0.178$.

Although the flushing action is taking place in the northeast branch of the lake, data for the table is that from Station 10. The station is so close to the channel that for all practical purposes the density structure can be considered the same. In the computation of $\Delta\rho / \rho_1$, ρ_1 is taken to be unity. The viscosities have been computed

* $\sigma_t = (\rho - 1)\, 1000$, where ρ is the specific gravity of water (Knudsen, 1901).

only approximately, since errors introduced of the order of less than 1 per cent are meaningless in the lake investigation.

TABLE 4

CRITICAL MIXING VELOCITIES

TABLE 4.1

	14 Mar 1951	22 Mar 1951	8 Oct 1951	31 Jan 1952	21 Mar 1952	14 Jan 1953	4 Feb 1953	18 Mar 1953
σ_{t1}	.10	.06	-.81	.15	.08	.12	.12	.10
σ_{t2}	.88	1.07	5.15	5.12	4.77	7.13	7.63	6.39
$\nu_2 \times 10^2$	1.47	1.47	1.14	1.44	1.39	1.27	1.27	1.28
$\Delta\rho \times 10^3$	.78	1.01	5.96	4.97	4.69	7.01	7.51	6.29
U_c	1.28	1.37	2.4	2.3	2.3	2.5	2.6	2.4

TABLE 4.2

	8 Oct 1951	31 Jan 1952	21 Mar 1952	14 Jan 1953	4 Feb 1953	18 Mar 1953
σ_{t1}	-.81	.15	.08	.12	.12	.10
σ_{t2}	2.03	2.39	3.42	6.39	7.03	6.38
$\nu_2 \times 10^2$	1.14	1.44	1.39	1.27	1.27	1.28
$\Delta\rho \times 10^3$	2.84	2.24	3.34	6.27	6.91	6.28
U_c	1.6	1.8	2.0	2.4	2.5	2.4

TABLE 4.3

	8 Oct 1951	31 Jan 1952	21 Mar 1952	14 Jan 1953	4 Feb 1953	18 Mar 1953
σ_{t1}	-.81	.15	.08	.12	.12	.10
σ_{t2}	.64	1.43	2.29	3.92	4.42	4.34
$\nu_2 \times 10^2$	1.14	1.44	1.39	1.27	1.27	1.28
$\Delta\rho \times 10^3$	1.45	1.28	2.21	3.80	4.30	4.24
U_c	1.42	1.46	1.75	2.03	2.12	2.11

Table 4 is divided into three sections, each using a different mean σ_{t2} for the computation of U_c; thus, in Table 4.1 the mean σ_{t2} is computed for the total salt layer, in Table 4.2 for the 4 m. below the interface, and in Table 4.3 for the 2 m. below the interface. Table 4.3 is subject to considerable error, due to the unreliability of the interpolated values.

In Table 4, computed U_c for two dates, 31 January 1952 and 4 February 1953, have been singled out for comparison with actual flushing velocities in the lake. The interface level and the amount of flushing is approximately the same in each case. The difference lies not only in the maximum density of the heavy salt water at the two different times but also in the density gradient. There is also a difference in the rate of flow for the two dates.

In Table 4.1 the increase of critical velocity for the two dates is from 2.3 cm./sec. to 2.6 cm./sec., or an increase of 13 per cent; in Table 4.2 the increase is from 1.8 cm./sec. to 2.5 cm./sec, or 39 per cent; in Table 4.3 the increase is from 1.5 cm./sec. to 2.0 cm./sec., or 33 per cent.

Since both in February 1952 and 1953 only relatively small impressions of short duration were made in the interface, it is assumed that at both times the actual velocities were close to the critical velocity. The relative increase in the rate of flow should, therefore, be similar to the relative increase in the computed critical velocities. The actual increase of flow in the two cases was from approximately 66 to 90 $m.^3$/sec., or approximately 38 per cent. This is in very good

agreement with the computed value of Table 4.2, where only the 4 m. below the interface were considered in the computation of the density.

The relative increase in critical velocities could have been obtained without knowing the actual value of Keulegan's mixing criterion. The following is a comparison between discharge rates, based on the value of $\Phi = 0.178$, and the appropriate cross-sectional area of the channel. In February 1952 and 1953 the interface was between 9 and 10 m. so that cross section "C" of Figure 11 should be used. It has an area of 2250 $m.^2$ and would give a mean velocity of 2.9 cm./sec., based on the flow of 66 $m.^3$/sec. in February 1952. This value is too high compared with the values of Table 4, but only 180 m. toward the main body of the lake, the cross-sectional area is almost twice that at "C" and remains approximately the same for the remainder of the northeast branch of the lake.

Therefore, using a cross-sectional area of 3700 $m.^2$, the velocity becomes 1.8 cm./sec. for February 1952 and 2.4 cm./sec. for 1953, when the discharge was 90 $m.^3$/sec. Both of these values are remarkably close to those computed in Table 4.2.

One more computation is made to check the validity of Keulegan's criterion in Lake Union. It is noted in Figure 10a that, following the flow peak of 66 $m.^3$/sec. at the beginning of March 1951, no additional salt water is added to the lake until after 14 March. This coincides with a dip in the flow curve. At the time of the next peak there is again no increase in salt water. Thus, one can set an upper and lower limit to the critical velocity.

In order to get a better idea of the actual daily flows, the following is a breakdown for the period in question. The rates of flow are all in $m.^3$/sec. Prior to 15 March 1951, the volumes were all above 53, with 54 on the 15th. On the 16th through 19th, the flows were 47, 44, 43 and 47. On the 20th, the flows went up to and stayed above 52 for the rest of the month, with the exception of the 28th and 29th when the flow was 24 and 18, respectively. These latter values produced the somewhat misleading dip in the average flow curve toward the end of the month.

These figures show that for the type of salt water in Lake Union on 14 March 1951, the critical rate of flow was between 47 and 53 $m.^3$/sec., and for 22 March between 47 and 52 $m.^3$/sec. The interface for the 14th is approximately at 14 m., and therefore a cross-sectional area of 4200 $m.^2$ should be used (Figure 11); for 22 March the interface is between 12 and 13 m., and therefore an area of 3800 $m.^2$ should be used. The velocity limits, then, for 14 March are 1.1 and 1.3 cm./sec., and for 22 March 1.2 and 1.4 cm./sec.

Table 4.1 (page 32) shows the values used for the computation of U_c. This time, however, since the salt layer is so shallow, the entire depth below the interface is considered in the computation of the mean σ_{t2}. The critical values obtained are 1.28 cm./sec. for 14 March and 1.37 cm./sec. for 22 March.

The evidence in favor of the criterion of mixing is not yet conclusive, since the increase in interface level might have been caused by high lockage operations.

Looking into lockage volumes for March 1951, one finds that during the first half of the month the volumes used were generally below 280,000 $m.^3$ per day, and during the second half of the month they were generally above 280,000 $m.^3$ per day. A particularly high period of lockage operations was 24 through 28 March, with an average volume of 370,000 $m.^3$ per day. During this period no water was wasted through the culverts, and yet the interface level did not rise but actually showed indications of a slight drop.

One can now conclude, therefore, that the flushing processes during March provide another excellent check, not only on the parameters used in but also of the value 0.178 used for the criterion of mixing.

One can also conclude that a discharge of 53 $m.^3$/sec. is not only sufficient to flush out any salt water that might flow into the lake, but that it might also be sufficient to prevent any salt water from reaching the lake.

3.5 FLUSHING AND THE CRITERION OF MIXING

The application of Keulegan's criterion of mixing checked remarkably well in the two cases of computations. As was mentioned before, the lake is similar in every respect to the model except that there was a density gradient in the pool of heavy liquid. Keulegan mentions that the criterion is only applicable to a "reach to be looked upon as a type of initial length." Even in this respect the model and the lake are similar, since the mixing is expected to take place only in 750 m. of the northeast branch of the canal. A similar type of mixing also is expected to take place in the northwest branch of the lake joining Fremont Canal.

Flushing has been shown by Keulegan to be an interfacial phenomenon in which internal waves break and the ejected eddies are carried away in the surface stream. This process of flushing is approached in the lake when the gradient below the interface is large, i.e., when considerable stability exists. As the gradient below the interface decreases, the mixing through the transition layers must be associated with momentum exchange of turbulent motion, as mentioned by Keulegan.

In the lake, even with large gradients, both mixing processes take place. It is, therefore, difficult to determine by the application of the criterion how far below the interface flushing would take place. Since by the process of momentum exchange a zone below the interface, the thickness of which depends upon the gradient, is set into motion, it is reasonable to choose the mean density of such a zone for application in the criterion. This essentially was done, with good results, by choosing layers 2 and 4 m. below the interface.

During the slow flushing of April and May of 1952 and 1953, the criterion of mixing called for a much greater rate of flow than actually took place. In each year both the density gradient below the interface and the velocity had decreased. This was probably a case where flushing by the ejection of eddies was modified by the process of momentum exchange.

One last important factor which enters into the flushing of Lake Union is the flushing time. Flushing of insufficient length occurred on four occasions: January 1951, November 1951, February 1952, and February 1953 (Figures 10a, 10b and 10c). Each time after the rate

of flow decreased, the interface level rose again. This is good evidence, as will also be shown in the next section, that flushing takes place in the northern portion of the lake and that the duration must be long enough to permit water from the southern portion of the lake to flow into the entrance and exit branches.

3.6 THE SLOPE OF THE INTERFACE

In conclusion of this chapter on the mixing and flushing of Lake Union, the wind effect on the process should be mentioned. In large bodies of water, and particularly in fresh-water lakes, wind circulation and mixing is an important factor which normally cannot be neglected. In highly stratified bodies of water such as Lake Union, wind circulation is principally restricted to the light surface waters, with mixing taking place at the interface. No investigations along these lines have been made in Lake Union; however, the isochlors were plotted in 1951 between Station 10 in the northern section and Station 8.5 in the southern section. This was done to determine the wind effect, if any, on the slope of the interface, but no correlation between wind and slope could be found. The slopes that might be produced, and probably are, by the wind blowing over the relatively short fetch would be too small to observe with the crude methods of sampling that were employed, especially as a differential barometer becomes less sensitive with great density difference.

Figure 12 is a rough plot of the isochlors between Stations 10 and 8.5, with no sampling between these stations. The profile shows that the northern section was considerably fresher than the southern

section. This correlates well with Figures 10a, 10b and 10c and indicates that flushing action takes place in the northern section. The figures also suggest that slopes produced by flushing action would overshadow any slope produced by wind action.

4. MONTLAKE CANAL

4.1 INTRODUCTION

Lake Union and Lake Washington are joined by a 4-km.-long dredged channel through Portage Bay, Montlake Canal, and Union Bay. The depth of the channel is everywhere between 9.5 and 11 m. until it reaches Webster Point where it rapidly drops off to 60 m. in Lake Washington (Figure 13). There are two major changes of direction. The first is a change from northeast in Lake Union to southeast in Portage Bay, and the second is at the west entrance to Montlake Canal where the direction changes to east. Other noteworthy features are the constriction at the University Bridge, which has a cross-sectional area of 1150 $m.^2$, and at the Montlake Canal, which is a straight channel 750 m. long with smallest cross-sectional area of 341 $m.^2$ At the west end, between Stations 15A and 15.1, the upper 6 m. of the canal widen into Union Bay; whereas below that depth the canal-like features are retained with a change of cross-sectional area from 92 $m.^2$ to 195 $m.^2$

Figures 10a, 10b and 10c show that the salt-water interface in Lake Union rose above the sill level of 10 m. between Lake Washington and Lake Union during the summer months, and that the possibility of salt intrusion into Lake Washington existed. In the autumn of 1952

current measurements were therefore made in Montlake Canal, together with chlorinity and temperature recordings using both the C-T-D recorder and bathythermograph (BT).

In the following sections the data will be presented and discussed. From the chlorinities in Montlake Canal, mixing rates will be computed and compared to results obtained by Keulegan (1949). The possible mechanism which permits the interface in Lake Union to rise above the sill level between Lake Union and Lake Washington will be considered.

4.2 DATA AND DISCUSSION

Figure 14 shows the chlorinity profile from Lake Union to Lake Washington for 30 October 1952, with the 0.5 $^{o}/oo$ isochlor used to indicate the fresh-salt-water interface. It can be seen that there is a slight drop of interface between Stations 10 and 12, between Stations 12 and 13.5, and a considerable drop from approximately 7 m. to 8 m. in Montlake Canal.

During the summer months when the fresh-water and salt-water temperatures in the canal system are almost the same, temperature is not a convenient indicator for the interface. However, in November the surface water has cooled sufficiently to make the difference distinct, and BT traces were used to indicate the interface depth. These show a general increase of surface water depths between Lake Union and Lake Washington, with the major dip occurring in the vicinity of Station 15 in Montlake Canal. Figure 15 shows the temperature profile of the canal for 21 November 1952, in which the drop of interface is approximately from 4 to 7 m. Table 5 below shows the results of current measurements and volume transports in the canal for 5 and 21 November 1952.

TABLE 5

STATION NO.	DATE 1952	TIME	INTER-FACE DEPTH m.	FRESH WATER		SALT WATER		NET DIS-CHARGE m.^{3}/sec.
				DISCHARGE m.^{3}/sec.	MEAN VELOCITY cm./sec.	DISCHARGE m.^{3}/sec.	MEAN VELOCITY cm./sec.	
14.2	5 Nov.	1300-1500	4	17.2	10	13.5	8	3.7
14.1A	21 Nov.	1200-1300	4	30.6	11	19.9	8.5	10.7
15.1	21 Nov.	1330-1400	7	---	--	12	10	--

On each day the net discharge as computed at the locks was 6 m.^{3}/sec. The current data observed on 5 November corresponds to a rise of interface in Lake Union, and the data obtained 21 November corresponds to a rapid fall (Figure 10b). On 21 November there is a large discrepancy in the salt-water discharge toward Lake Washington obtained at Stations 14.1A and 15.1. Also, both on 5 and 21 November the net discharge through the canal did not agree with the net flow obtained from the locks.

On the basis of continuity, the salt discharge at Station 14.1A should be the same as at Station 15.1. The discrepancy is large, possibly due to excessive mixing, erroneous current measurement, current variations, or non-representative measurement. Mixing, as will be shown in section 4.3, can account for only 1 to 2 m.^{3}/sec., which is considerably less than the difference observed.

Error in current measurement may be introduced by boat motion during the observation period. At Station 14.1A the small boat (5 m. long)

was held in mid-channel by an anchor and a rope tied to the cement bulkhead of the canal. Its motion compared to the measured current velocities would cause only small error. At Station 15.1 conditions were slightly different. The boat was again anchored in mid-channel but tied to a buoy instead of a bulkhead. Station 15.1 is more exposed than Station 14.1A, and yawing is hard to prevent. This becomes important when velocities less than 2 or 3 cm./sec. are to be measured. However, salt-water velocities were considerably larger than this, and it is improbable that errors were large enough to cause the observed discrepancy. As mentioned in section 1.4, the electrically-indicating meter in the case of yawing would give irregular contact clicks. These were not observed at either station.

Finally, the discrepancy could be due to fluctuations in current velocity. Variations of velocity as high as 6 cm./sec. have been observed for different times at the same depth. BT temperatures taken at Stations 14.1A and 15.1 during the day of 21 November (see Appendix B) indicate temperature variations of 0.3° C. in the interfacial zone. These observations strongly indicate fluctuations in current velocity large enough to cause differences of discharge rates of the magnitude observed.

If net discharge rates computed on the basis of current measurements are compared with those obtained at the locks, which are computed on an average daily basis, then the assumption is made that a current profile of a Montlake Canal station is representative of the mean daily discharge. This assumption, of course, is erroneous if the discharge is predominantly due to lockage operations, as in November 1952 when

the salt-water siphon was shut down. Considering that a fresh-water disturbance due to filling the large lock is similar to a solitary wave in shallow water of 10 m. depth (section 2.5), then a variation in surface current velocities would be noticed in only 15 minutes after a lockage. Therefore, the discrepancies between net daily discharge, computed on the basis of current measurements, and that obtained from the locks is probably due to variations in lockage operations.

Finally, it should be mentioned that the addition of cold water (Figure 15) between 6 and 7 m. at Station 15.1 is due to surface cooling of the shallow Union Bay.

4.3 MIXING RATE

In the paper on critical mixing velocities discussed in section 3.4, Keulegan also derives a law of mixing rate which in simplified form is:

$$U_m = 3.5 \times 10^{-4} (U - 1.15\, U_c).$$

U_m is the volume of heavier liquid that crosses unit area of the interface in unit time; U is the velocity of the lighter liquid; and U_c is the critical velocity defined in section 3.4.

With the data obtained by means of the C-T-D recorder it is possible to check this mixing law. On 30 October 1952 the increase of chlorinity from Station 15.1 to Station 14.1 in Montlake Canal was 1.6 kg. per fresh-water column of 1 m.^{2} area, taking the change of cross-sectional area into consideration.

On the basis of a viscosity of 1.2×10^{-2} poise, a density difference of 3×10^{-3} g./cm.^{3}, and a criterion of mixing as previously used $\Phi = 0.178$, $U_c = 1.8$ cm./sec. The velocities in the canal were not measured 30 October, but from the net discharge of 6 m.^{3}/sec. one can assume an approximate salt discharge into Lake Washington of 6 m.^{3}/sec. and a fresh-water discharge of 12 m.^{3}/sec. This gives a relative velocity of 12 cm./sec., with the interface at 7 m. From these data one obtains, according to the law of mixing, $U_m = 35 \times 10^{-4}$ cm./sec., or, from an approximate chlorinity of the salt water of 3 ‰, a salt injection of 105×10^{-6} kg./m.^{2}/sec. From the distance of 700 m. between Stations 14.1 and 15.1 and the mean surface velocity of 4 cm./sec., one finally obtains an increase of chloride of 1.8 kg. per fresh-water column of 1 m.^{2}, which is in excellent agreement with the observed increase of chloride.

On the basis of this result one can now estimate the discharge of salt water through the interface in Montlake Canal (30 October 1952). With $U_m = 35 \times 10^{-4}$ cm./sec. and an interface area at 7 m. in the canal of 24,500 m.^{2}, one obtains a salt discharge into the fresh surface water of about 0.9 m.^{3}/sec.

One obtains from the mean velocities at Station 14.1A (21 November 1952) $U_m = 63 \times 10^{-4}$ cm./sec. and a discharge across the interface (31,500 m.^{2} at 4 m.) of about 2 m.^{3}/sec.

The rate of mixing can be estimated roughly for the stretches of canal through Portage Bay and Union Bay. If salt water continues to flow through the deeper dredged channels at about 4 cm./sec., then one can expect a rate of mixing of about 0.5 m.^{3}/sec. between Lake Union and Lake Washington on either side of Montlake Canal.

The above results show that mixing is an important factor which must be considered in dynamic computations applied to the canal. It is also interesting to note that a canal of the dimensions of Montlake Canal, 6 km. long, would be sufficient to prevent salt intrusion into Lake Washington.

4.4 MECHANISM CONTROLLING THE INTERFACE HEIGHT IN LAKE UNION

Figure 10b shows that in 1952 the interface level in Lake Union rose steadily throughout the summer until 14 November. Upon reaching 7 m. the salt water had sufficient energy to maintain a flow into Lake Washington, as was observed in October and again in December. In order to explain the continued rise of interface, a mechanism must have existed by which all the water which entered Lake Union was not able to flow into Lake Washington. The data show (section 4.2) that there was a slight drop of interface between Stations 10 and 12, Stations 12 and 13.5, and a major drop in Montlake Canal. The latter resembled an internal hydraulic jump, as investigated by Stommel and Farmer (1952). Their results, however, do not apply to Montlake Canal, since the critical velocities necessary for the existence of a jump were not reached.

Stommel and Farmer also neglected to consider mixing across the interface, which was shown to be of importance in the previous section. The only other mechanism able to maintain a salt-water head in Lake Union is friction along the boundary of the two fluids.

By this mechanism one can also explain the sudden drop of interface in Lake Union. Lockages which caused the major discharge while the salt-water siphon was closed down were low on three separate days after

14 November (section 3.3); therefore, the frictional stress due to fresh-water discharge permitted more salt water to flow into Lake Washington.

The drops of interface occurred at the constrictions because here the larger fresh- and salt-water velocities increase the stress between the liquids. Superimposed upon this is the reduction due to mixing across the interface.

Data available are insufficient to establish the relation between the interface level in Lake Union, fresh-water discharge, and salt intrusion into Lake Washington. From previous observations it can be stated that with a net discharge of 9 $m.^3$/sec. and an interface at 8 m. no salt intrusion into Lake Washington takes place, as was observed in July and August 1951 and 1952.

5. SALT-WATER INTRUSION AND FLUSHING OF LAKE WASHINGTON

5.1 INTRODUCTION

Lake Washington (Figure 1), located just a few kilometers from Puget Sound on the eastern edge of Seattle, is 29 km. long and is oriented in a north-south direction, with an approximate area of 90 $km.^2$ and a maximum depth of 65 m.

The main tributaries are the Cedar and Sammamish Rivers entering at the south and north end of the lake, respectively. The minimum discharge of each river is approximately the same, being less than 3 $m.^3$/sec. and occurring in either August or September. The maximum discharge of the Cedar River is between 55 and 140 $m.^3$/sec. and that of the Sammamish

River 20 to 50 $m.^3$/sec., occurring in February or March (unpublished U. S. Geological Survey data, 1950 to 1952).

The limnology of the lake has been discussed by Sheffer and Robinson (1939). Lake Washington is a typical fresh-water lake, with minimum temperatures approximately 6° to 8° C. depending on the climatic conditions of the year. Because of these high minimum temperatures the lake overturns during one extended period each year, beginning approximately in December and lasting through February or March. After March the lake rapidly becomes stratified, with maximum surface temperatures of 20° to 25° C. during August.

Chlorinities reported in early studies of the lake were very low. Sheffer and Robinson (1939) reported approximately 2 p.p.m. (parts per million) in 1933, while in the data listed by Smith and Thompson (1927) the chlorinity did not exceed 4 p.p.m. The latter authors also listed the total salt analysis of J. G. Priestley, chemist for the city of Seattle, from which the sulfate-chlorinity ratios were computed to be 4.2 for the north end of the lake and 6 for the south end which is under the Cedar River influence. These ratios are typical for fresh water, and it is safe to say that at least until 1933 there was no appreciable salt-water intrusion into Lake Washington.

The following paragraphs will show that during the past few years the chlorinity of the lake has materially changed. After discussion and evaluation of the data, therefore, lake overturn with brackish water at the bottom will be discussed, the salt budget will be determined, and, on the basis of the annual flushing rate, computations will be made to show the seriousness of salt-water intrusion into Lake Washington.

5.2 CHLORINITY DATA AND EVALUATION

Since the beginning of the survey, the minimum chlorinity found in Lake Washington at any time was at least five times the maximum found by Smith and Thompson (1927). During the autumn months there was a higher chlorinity layer at the bottom of the lake.

The sulfate-chlorinity ratio was again determined in February 1953, when the chlorinity was 73 p.p.m., and found to be 0.081. This is below 0.139, the ratio for sea water (Thompson, Johnston, and Wirth, 1931), and definitely not that commonly found in fresh waters.*

Figure 16 shows the chlorinity profile at Station 18 for October 1950, 1951 and 1952. For each succeeding year both the maximum chlorinity at the bottom and the height of the brackish water layer increased.

With the relatively high chlorinity of 200 p.p.m. at the bottom of the lake in October 1952, special attention was given to the chlorinity variation at 60 m. for the remainder of the year. Figure 17 shows this variation of chlorinity, temperature, and σ_t. There was a decrease of chlorinity at 60 m. between 9 and 14 October, after which it rose to a maximum 24 November. The chlorinity then began to decrease steadily toward January, with the exception of a small increase between 18 and 23 December.

Figure 18 shows the chlorinity profile at Station 18 for various times during the autumn of 1952. By 24 November the chlorinity at 60 m. had reached a maximum of 252 p.p.m., which decreased to 225 p.p.m. by

---

* Sea water before flowing into Lake Washington passes through Lake Union where, by bacterial reduction of the sulfate into sulfide, the sulfate concentration is reduced and can cause the low sulfate-chlorinity ratio (Obara, 1951).

23 December. The surface chlorinity increased from 20 p.p.m. in October to 40 p.p.m. in November and then to 65 p.p.m. in December. The figure also shows that the lake water had become homogeneous by 28 January 1953, with a chlorinity of 80 p.p.m.

The total chloride content of the lake, computed from the survey data taken at Station 18 from July 1952 until November 1953, is plotted in Figures 19a and 19b. It rises steadily throughout the autumn months of 1952 and reaches a maximum of 230,000 tons at the end of January, after which time it decreases. There are some irregularities in the curve, however. In December and again in January there are large apparent decreases of total salt in the lake, although there was no large-scale flow through the lake until 7 January 1953 (Figures 10b and 10c). Then, again, there is an increase of total salt after the April minimum, although there was no addition of salt water from Lake Union. The interface in Lake Union was below 10 m. at this time, and the possibility of salt-water intrusion by slugs is improbable because of the changes in direction of the canal between the lakes (section 4.1).

Finally, comparing Figures 17 and 19a and 19b, it should also be noted that the chlorinity at 60 m. decreases after 24 November while the total amount of salt is still increasing in the lake.

Station 18, upon which the chlorinity of the lake is based, lies 0.3 mile off Madison Park and is approximately 1 mile south of Webster Point, the termination of the ship canal and a location where major changes such as salt intrusion and flushing would be felt first (Figures 1 and 2). An explanation, therefore, for the fluctuations of chlorinity at 60 m. (Figure 17), which correlates well with the interface

level in Lake Union for the same period (Figures 10b and 10c), is that salt water flows into the lake more rapidly than it distributes evenly through the bottom layers. Thus, the chlorinity at 60 m. of Station 18 is not the same as at other parts of the lake. The rapid chlorinity decrease at 60 m. after 24 November 1952 thus was not necessarily due to overturn or wind mixing.

Station 18 also lies in direct line between the Cedar River mouth and the canal. When the fresh-water flow through the system is large, as in winter and spring, one might sample water of lower chlorinity than is to be found in the rest of the lake. Thus, if the chlorinity sampled at Station 18 during winter and spring is 10 p.p.m. lower in the surface 15 m. than at other parts of the lake, the calculated total chloride would be 12,000 tons in error. The actual chlorinity difference might have been considerably greater than 10 p.p.m., resulting in an apparently low total chloride content of the lake during April and May, and again during August and September 1953 (Figure 19b).

Since turnover cannot be assumed similar in all parts of the lake, the total salt error is particularly large at that time, especially with high winds such as the 14 m./sec. on 7 January 1953.

5.3 BRACKISH WATER AND LAKE OVERTURN

With the intrusion of salt water into Lake Washington, the problem arises as to what concentration of chlorinity of the bottom water will prevent overturn and cause stagnation of the brackish water accumulating at the bottom.

With a view of answering these questions, the temperature variation in the lake was closely watched. Figure 20 shows the temperature at Station 18 for various times during the autumn of 1952. The curve for 13 August 1952 shows the temperature before salt intrusion took place. Surface cooling was noted as early as 9 October. Minimum temperatures in each case were found between 40 and 50 m., with increasing temperatures below that depth. These minimum temperatures showed a tendency to increase, probably due to salt-water intrusion, until 5 December when the fresh surface water had become only slightly cooler than the brackish water. By 23 December the minimum temperature had decreased again, due to overturn, being approximately the same as the fresh surface water. By 28 January 1953 the lake was completely mixed, with a temperature of 7.6° C. and a chlorinity of 80 p.p.m. The curves also show that until 23 December convective overturn had not been able to replace the brackish water at the bottom of the lake, although intermediate depths were affected.

Figure 20 shows that on 23 December water of $\sigma_t = -0.04$ had replaced the warmer water found at 45 m. on 5 December but had not yet replaced the water at 60 m. of $\sigma_t = 0.12$. The density difference between the mixed surface water and that at 60 m. was 0.16×10^{-3}, and wind circulation had not yet overcome the slight stability. By 28 January 1953 mixing of the lake was complete, and water with $\sigma_t = 0.05$ had replaced the slightly denser water of $\sigma_t = 0.12$ found at 60 m. on 23 December 1952. This demonstrates that processes other than thermally-induced convection are involved in the process of lake overturn.

Ruttner (1953) points out that the thermal density gradient at higher temperatures is much greater than close to temperatures of maximum density. Thus, in summertime with high stability, there is an independent circulatory system in the warm surface water; but in winter, as cooling takes place, the stability breaks down and the wind effect is felt at ever greater depths.

In Lake Washington, as is generally true of non-ice-covered lakes in similar latitudes, minimum stability coincides with the stormy season of the year. Therefore, water of greater density than that due to winter cooling can be permitted to accumulate at the bottom of the lake without causing stagnation. However, the permissible excess density has not been determined and depends to a large extent upon the wind-generated circulation.

To obtain an idea of the possible limits involved, reference is again made to Ruttner who mentions Ulmener Maar, a meromictic lake which has a salinity of 185 mg./L. in the upper and about 500 mg./L. in the deeper strata. Increase in density due to difference in concentration is several times greater than the decrease brought about by a temperature rise from 5.4° C., the minimum surface temperature, to 7.2° C. in the lower layer. The density gradient provided sufficient stability to prevent complete overturn at a time when it should occur.

5.4 THE SALT BUDGET

While it is possible to add considerable amounts of salt to the lake and increase the chloride concentration at the bottom to more than 200 p.p.m. without causing stagnation, the continued increase of

total salt might cause serious trouble. Both fresh-water life and communities along the lake who plan to use the water for drinking purposes could be affected.

To obtain a qualitative picture of the flushing process, the year can be divided into two flushing periods, the dry summer season and the rainy winter season. It should also be remembered that the canal through which all water must flow out is only about 10 m. deep, and therefore the outflowing water is lake surface water.

The dry season of the year, as far as the flushing of the lake is concerned, extends from the beginning of July until the end of October. During this period, the flow out of the lake necessary for the operation of locks and siphon is a relatively small amount of about 850,000 $m.^3$ per day. Since this is in the period of thermal lake stratification, the circulation is confined only to the surface layers, and water of possibly higher chloride concentration below the thermocline is unaffected.

Increased precipitation resulting in a rising lake level makes it possible for the engineers at the locks to waste water over the spillways, usually by the end of October or beginning of November. This, then, is the beginning of the winter season. It will continue to a varying degree throughout winter and spring until approximately the end of June (Figures 10a, 10b and 10c). Wastage depends upon runoff into the lake and the lake level. During some months of the winter period, usually January and February, flushing exceeds that for the entire summer season, with active lake overturn and wind mixing taking place.

The validity of basing the total chloride content of the lake on the information of just one station has been questioned above, but at certain times of the year the information should be quite reliable and will have to be used to obtain annual flushing rates. The most reliable time is in December or January when the lake has become homogeneous due to overturn and wind mixing and before too much water has been discharged (see 28 January 1953, Figures 18 and 20).

The other time would be in July after wastage of water has ceased and thermal stratification has set in. The major portion of the lake below a thin, warm surface layer would then be unaffected by wind and come to equilibrium.

Table 6 below shows the maximum and minimum total chloride of the lake for the 3 years of the survey, based on Station 18 data, with reliable winter and somewhat doubtful summer values. The per cent flushing shown is only that for the winter season discussed above and does not include the summer period. The rate of flushing, therefore, is a few per cent below the annual rate.

To check the flushing, one can also compute the amount of salt taken out of the lake from the monthly rates of flow through the system and the mean monthly chlorinity of the upper 15 m. in Lake Washington.

TABLE 6

DATE	TOTAL Cl 1000 tons	PER CENT FLUSHING
27 December 1950	88	17
24 July 1951	73	
19 December 1951	102	20
18 July 1952	81	
28 January 1953	230	20
15 July 1953	183	

Table 7 shows the total amount of flow and tons of chloride removed from the lake during the first 6 months of 1953. The values are plotted on Figure 19b. The curve starts with a maximum amount of 230,000 tons 7 January 1953, when it is assumed that salt intrusion ceased. The curve based on Station 18 meets the curve based on the canal flow in July and again in November. It is safe to assume that the total salt based on the flow through the system is the more reliable.

From Table 7 one can also predict that during the dry months, August through October, the rate of flushing will be approximately 1500 tons per month. Assuming that the discharge from the lake in November and December is approximately the same as in April and May, the final chloride in the lake will be between 170,000 and 180,000 tons, provided there is no salt intrusion into the lake (which, indeed, if it took place at all, was not indicated by the data). The rate of flushing for 1953 will have been 24 per cent. This value is higher than that for the previous years, since it was computed on a 12-month basis rather than a 6-month basis.

TABLE 7

MONTH 1953	FLOW IN 10^6 m.^{3} PER MONTH	FLUSHING IN 1000 tons Cl
January	158	12.8
February	167	13.1
March	76	4.0
April	79	4.5
May	82	4.9
June	62	3.7
July	31	1.8

Evidently only about 25 per cent of the total salt is removed from the lake annually. This is a reasonable figure when one considers that the annual flow through the lock system is approximately 30 per cent of the lake volume. On the basis of 25 per cent flushing, the amount of salt which can be permitted into the lake without increasing the total salt content and the time required to reduce the salt content to the 1950 level, provided no additional amount of salt is permitted to enter the lake, can be computed.

If B is the amount of salt that may be permitted to enter the lake and A is the amount of residual salt before B enters, and also at the end of the following flushing period, then $A = 0.75\ (A + B)$ or $B = 0.33\ A$.

If one considers the residual amount of chloride for 1952 to be 80,000 tons (July 1952), then the permissible amount of salt B would

have been 27,500 tons. The amount that actually did flow in was 150,000 tons, or approximately five times the permissible amount.

If R is the residual amount of salt water after n years when A is the present residual salt, then $R = 0.75^n A$, provided no additional salt enters the lake.

Again, if one considers A for 1953 to be 175,000 tons and that we wish R to be 50,000 tons, which corresponds to a chlorinity throughout the lake of 20 p.p.m., then according to the second formula it would take 4 to 5 years to attain this chlorinity, provided no additional salt enters the lake.

5.5 CONCLUSION

The foregoing analysis of lake overturn and flushing applies only so long as a critical amount of salt intrusion is not exceeded. A concentration of salt water greater than the critical value would prevent overturn and cause stagnation. The salt would thus be withdrawn from the lake's flushing action. The critical chloride concentration is not known, and it depends on the wind circulation and to some extent on the salt concentration of the surface waters. Figure 16 indicates that further salt-water intrusion, similar to that of 1952, could raise the interface level to 35 m. and increase the maximum chlorinity to 250 p.p.m. Both the maximum chlorinity and the temperature difference would be similar to the permanently stratified Ulmener Maar.

The computation of the last section shows that a small amount of salt can be permitted to intrude into the lake without causing a permanent increase in total chloride of the lake.

Finally, the computation regarding salt reduction in the lake shows that it takes several seasons to flush the lake of an amount of salt which might intrude in a matter of a few months. In other words, salt intrusion of the magnitude of 1952 should not be permitted more than once every 5 or 6 years.

6. CONCLUSION

6.1 SUMMARY

Lake Washington is connected to Puget Sound by means of Salmon Bay, Fremont Canal, Lake Union, and Montlake Canal. Salmon Bay and Lake Union are both deeper than the two canals, which are approximately 10 m. deep, and therefore provide catch basins for the sea water which enters through the locks.

In section 2 it is shown that water from a depth below 8.5 m. in Salmon Bay is introduced through culverts at the bottom of the locks. Upon opening the upper gates, the diluted sea water flows into Salmon Bay and is replaced by lake surface water. Three distinct flows are to be noticed in Salmon Bay when the large lock is operated: first, a seaward set or a marked reduction of landward set in the bottom salt layers when the lock is being filled; secondly, a strong seaward current in probably all waters after the upper gates are opened; finally, a salt-water landward surge at the bottom of Salmon Bay and Fremont Canal.

From the depth of the filling culvert and the upper miter sill, it was possible to compute the minimum and maximum volumes of intruding salt water. These did not differ by much and were roughly twice the

volume used in raising the water level in the lock from sea to lake level. It was also pointed out that the amount of fresh water used in each lockage operation is independent of the sea level.

The salt-water siphon and the Salmon Bay basin were shown to be inadequate on the basis of volume capacity and because the salt water flowing lakeward out of the lock travels essentially as a jet. The slug of salt water will have sufficient energy to overcome the slight rise through Fremont Canal and spill into Lake Union where it is no longer available to the siphon's flushing action.

Lake Union provides a catch basin for the intruding salt water. During the summer season when the runoff through the canal system is at a minimum, the interface level rises to above the sill level between Lake Union and Lake Washington so that salt intrusion into Lake Washington can take place. With an excess amount of water available during winter and spring, some flushing of the lake takes place, depending upon the rates of flow. A discharge of more than 100 $m.^3/sec.$ which occurred in February 1951 and lasted for 13 days was sufficient to flush the lake completely. It was also shown that a discharge of 50 $m.^3/sec.$ was sufficient to prevent a rise of interface in Lake Union.

Montlake Canal, because of the small cross-sectional area, increases the velocity of the fresh water flowing seaward. This increase in velocity causes sufficient mixing to materially reduce the amount of salt water flowing toward Lake Washington. It is also believed that the increased velocity in the constrictions between the two lakes by frictional stress maintains the interface at above sill level in Lake Union.

From chlorinity data and in 1952 by direct observation in Montlake Canal, salt intrusion into Lake Washington was shown to occur in early autumn. Winter cooling reduces the stability of the lake sufficiently so that wind mixing becomes an important factor in the prevention of permanent stratification due to salt water in the bottom layers of the lake. Although the critical chlorinity which would prevent overturn in these bottom layers was not obtained, it was shown by comparison to another meromictic lake that critical chlorinities were almost reached in 1952. From total chloride computations and discharge it was shown that only 25 per cent of the salt in the lake would be flushed out annually, the process of flushing being simply that of winter overturn which mixes the salt from the bottom layers into the discharging surface waters.

6.2 APPLICATION OF MODEL STUDIES

On the basis of model studies by O'Brien and Cherno, it has been estimated that the initial velocity of the salt water leaving the large lock is 47 cm./sec. and that final velocity upon reaching Lake Union is still 0.6 to 0.7 per cent of the initial velocity, depending upon whether only the half or the full chamber is being used. Salt water would therefore reach Lake Union in 2 to 3 hours.

Although the measurements made in Fremont Canal were insufficient to check the model results, evidence of salt intrusion, in spite of a high fresh-water discharge, lends support to the assumption that the studies of O'Brien and Cherno are applicable to Fremont Canal.

Application of Keulegan's model studies of mixing to both Lake Union and Montlake Canal shows that the criterion of mixing and the law of mixing rate hold for larger systems. One can also conclude that the mixing process, namely the breaking of internal waves and ejection of eddies from the denser to the lighter liquid, takes place in larger systems.

The results of Keulegan's work are applicable not only to systems such as the Lake Washington Ship Canal but also to the initial stages of mixing in river estuaries.

6.3 FREMONT AND MONTLAKE CANALS

In both the Fremont and Montlake Canals with their relatively small cross-sectional area, the fresh-water velocities are necessarily increased and, therefore, maximum mixing is expected to take place. In Montlake Canal where salt intrusion into Lake Washington occurs, 1 to 2 $m.^3/sec.$ pass from the salt water into the surface water and are carried seaward. In Fremont Canal this rate would be somewhat larger, due to the velocity of the salt-water slug.

The minimum fresh-water discharge necessary to prevent salt intrusion through Fremont Canal is between 50 and 60 $m.^3/sec.$, based on a mixing rate of 5 to 6 $m.^3/sec.$ This is approximately the same value as obtained in March 1951 when the interface level in Lake Union did not rise. For Montlake Canal the minimum discharge to prevent salt intrusion into Lake Washington is approximately 9 $m.^3/sec.$ when the interface in Lake Union is at 8 m.

6.4 RECOMMENDED FUTURE INVESTIGATIONS

The information obtained from survey data is sufficient to make approximate computations only. In order to check O'Brien and Cherno's model experiments and to obtain sufficient information so that salt-water intrusion into Lake Washington can be predicted, measurements must be made under more controlled conditions.

For Fremont Canal it would be of interest to know the rate of advance of the salt-water slug and also the time it takes to reach Lake Union. This can be done by current measurements which will provide an accurate current profile in no more than 10 minutes. It could also be done by conductivity recordings taken simultaneously at two or more stations in the canal. For each method, the filling time of the lock and the opening time of the upper lock gate are of importance.

For Montlake Canal a faster method of current measurement is also necessary, again well correlated with the opening of the upper lock gate and the interface level in Lake Union.

Finally, the presence of chloride in Lake Washington provides an excellent tracer in the determination of lake circulation, both vertical and horizontal, under differing wind conditions. This would be of great value, not only in pollution studies but perhaps in providing sufficient information to determine the critical salt-water concentration at the bottom of the lake which would prevent overturn.

Generally, measurement of chlorinity by conductivity and temperature by thermocouple is recommended in waters of low concentration. Sampling becomes more accurate and faster where gradients are of

importance. Another advantage is that continuous recordings of chlorinity variation can be made. After a cell is calibrated and a nomograph constructed, reduction of data is faster than by conventional methods of titration.

BIBLIOGRAPHY

Fries, F. E. and A. G. Viney
1933. Hydraulic Model Test of Lake Washington Ship Canal. Unpublished Master's thesis, Univ. of Calif., Berkeley, Calif.

Keulegan, G. H.
1949. Interfacial Instability and Mixing in Stratified Flows. J. Research Nat. Bur. Standards, 43: RP-2040.

Kincer, J. B.
1941. Climate and Weather Data for the United States. Climate and Man, U. S. Dept. of Agriculture, Washington, D. C.

Knudsen, Martin
1901. Hydrographical Tables. G. E. C. Gad, Copenhagen, Denmark.

Obara, Nobuhiko
1951. The Significance of Sulfate Anomaly as an Indicator of Stagnation of Sea Water in a Bay. J. Geogr. Tokyo, 60: 173-175.

O'Brien, M. P. and John Cherno
1932. Model Law for Motion of Salt Water through Fresh. Proc. Am. Soc. Civil Eng., 58: 1769-1788.

Ruttner, Franz
1953. Fundamentals of Limnology. Translated by D. G. Frey and F. E. Fry, Univ. of Toronto Press, Toronto, Canada.

Sheffer, V. B. and R. J. Robinson
1939. A Limnological Study of Lake Washington. Ecol. Monogr., 9: 95-143.

Smith, E. V. and T. G. Thompson
1927. Salinity of the Lake Washington Ship Canal. Eng. Expt. Sta. Bulletin no. 41, Univ. of Wash., Seattle, Wash.

Stommel, Henry and H. G. Farmer
1952. Abrupt Change in Width in Two-Layer Open Channel Flow. J. Mar. Res., 11: 205-214.

Thompson, T. G., W. R. Johnston and H. E. Wirth
1931. The Sulfate-Chlorinity Ratio in Ocean Waters. J. du Conseil, 6: 246-252.

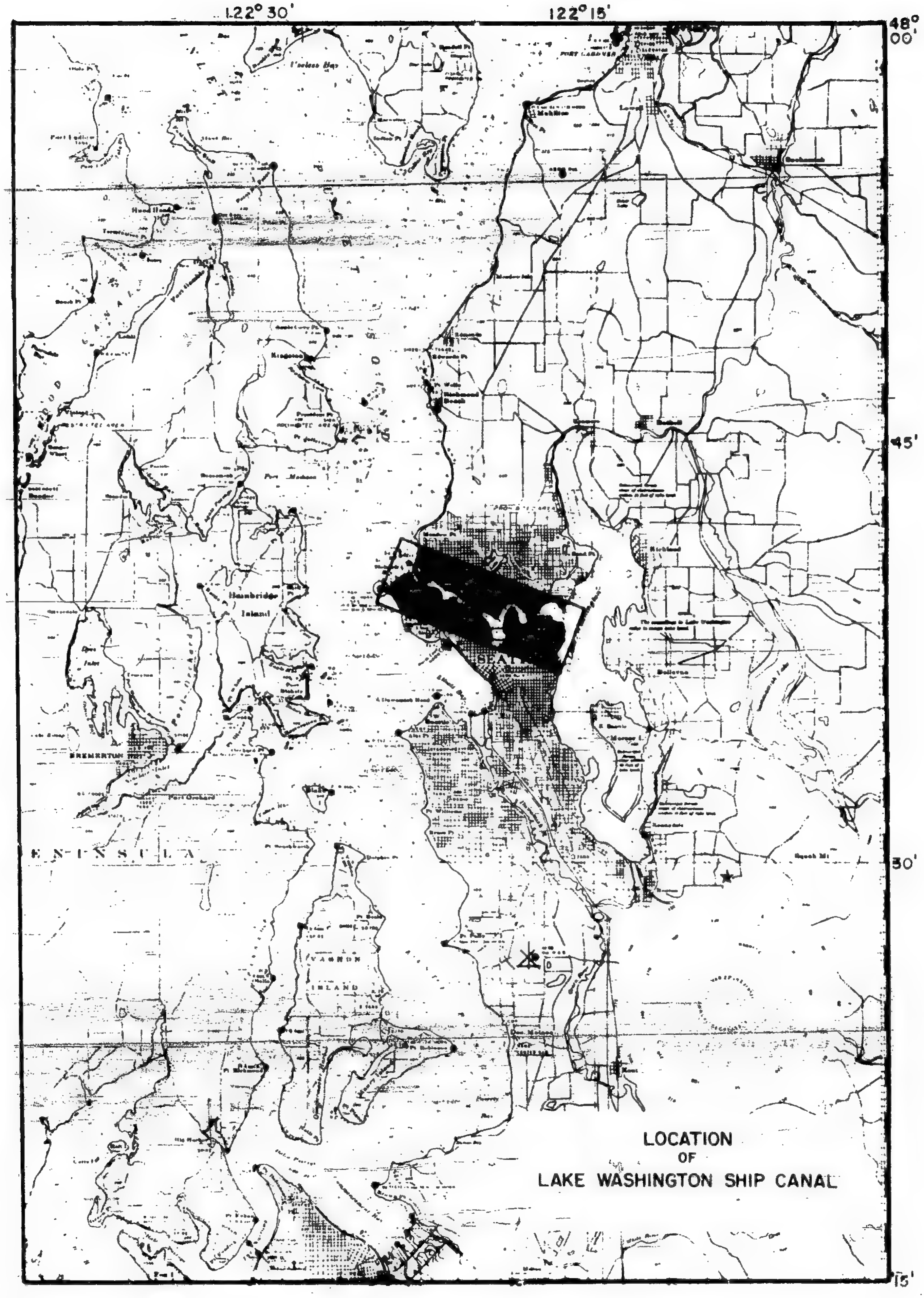


FIGURE 1. Location of the Lake Washington Ship Canal in Relation to Puget Sound and Lake Washington. (Base Chart U.S.C.&G.S. Chart 6401)

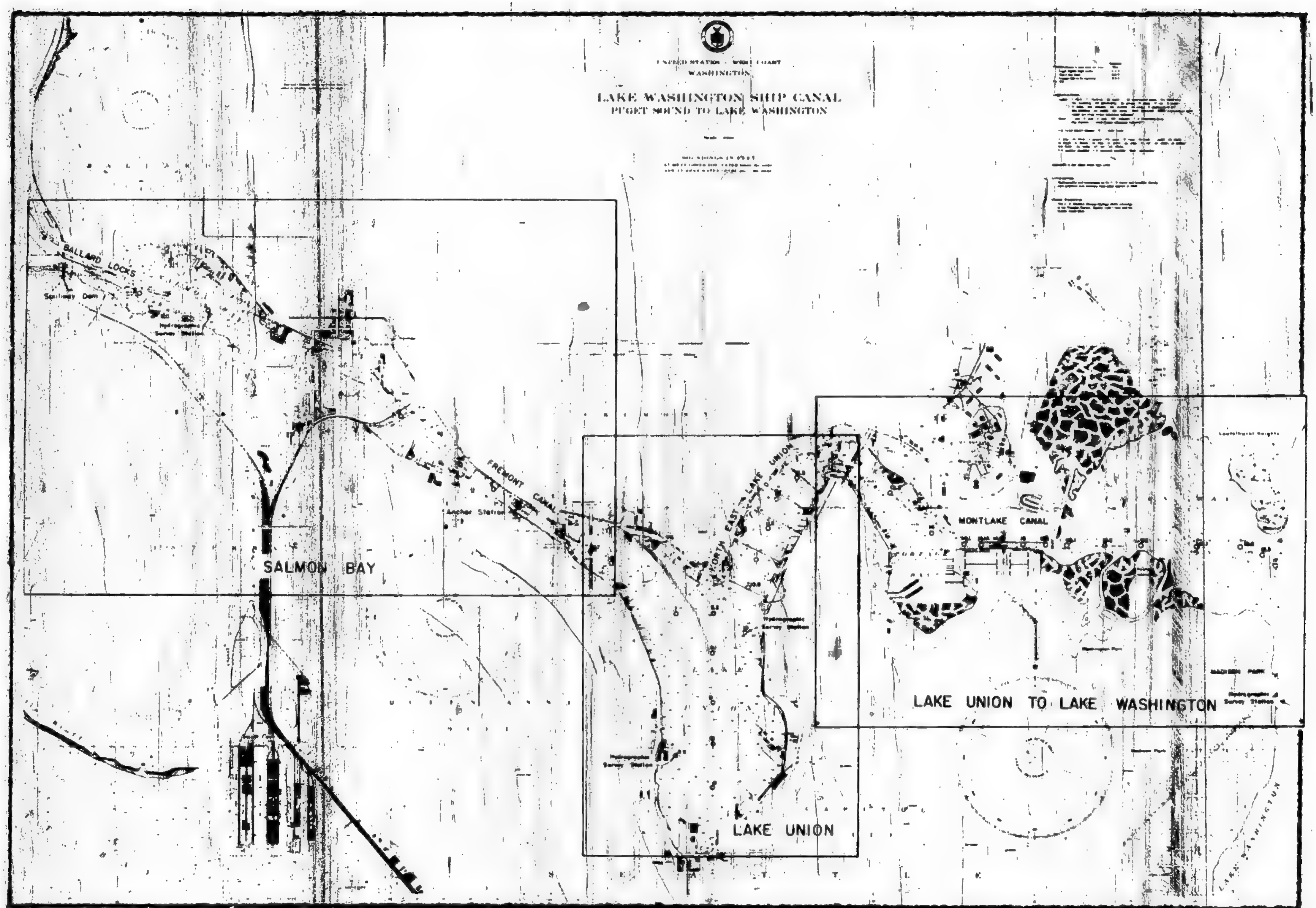


FIGURE 2. Lake Washington Ship Canal Showing Survey Station Numbers and the Three Sections as Used in this Study.

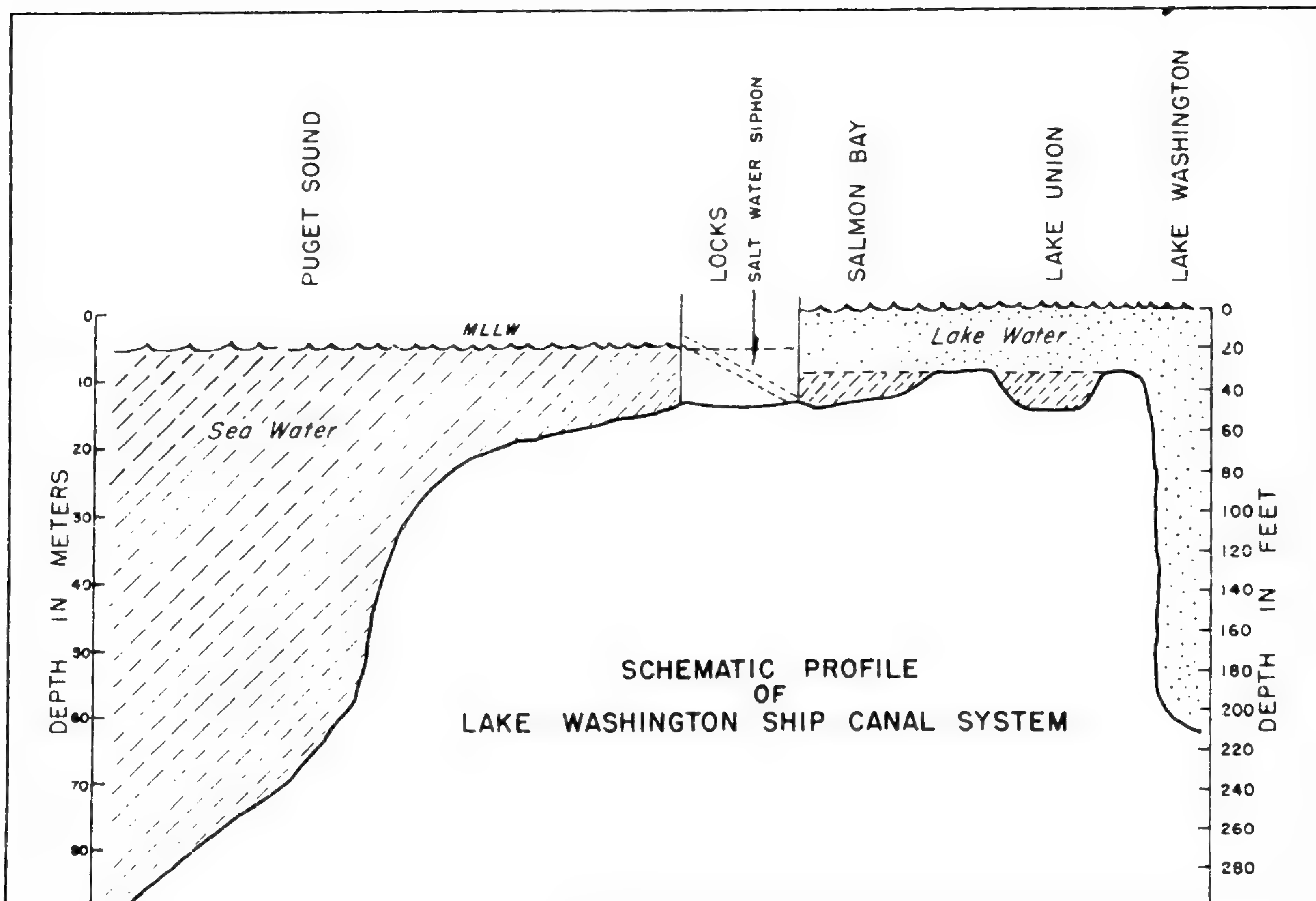


FIGURE 3. Schematic Profile of the Ship Canal.

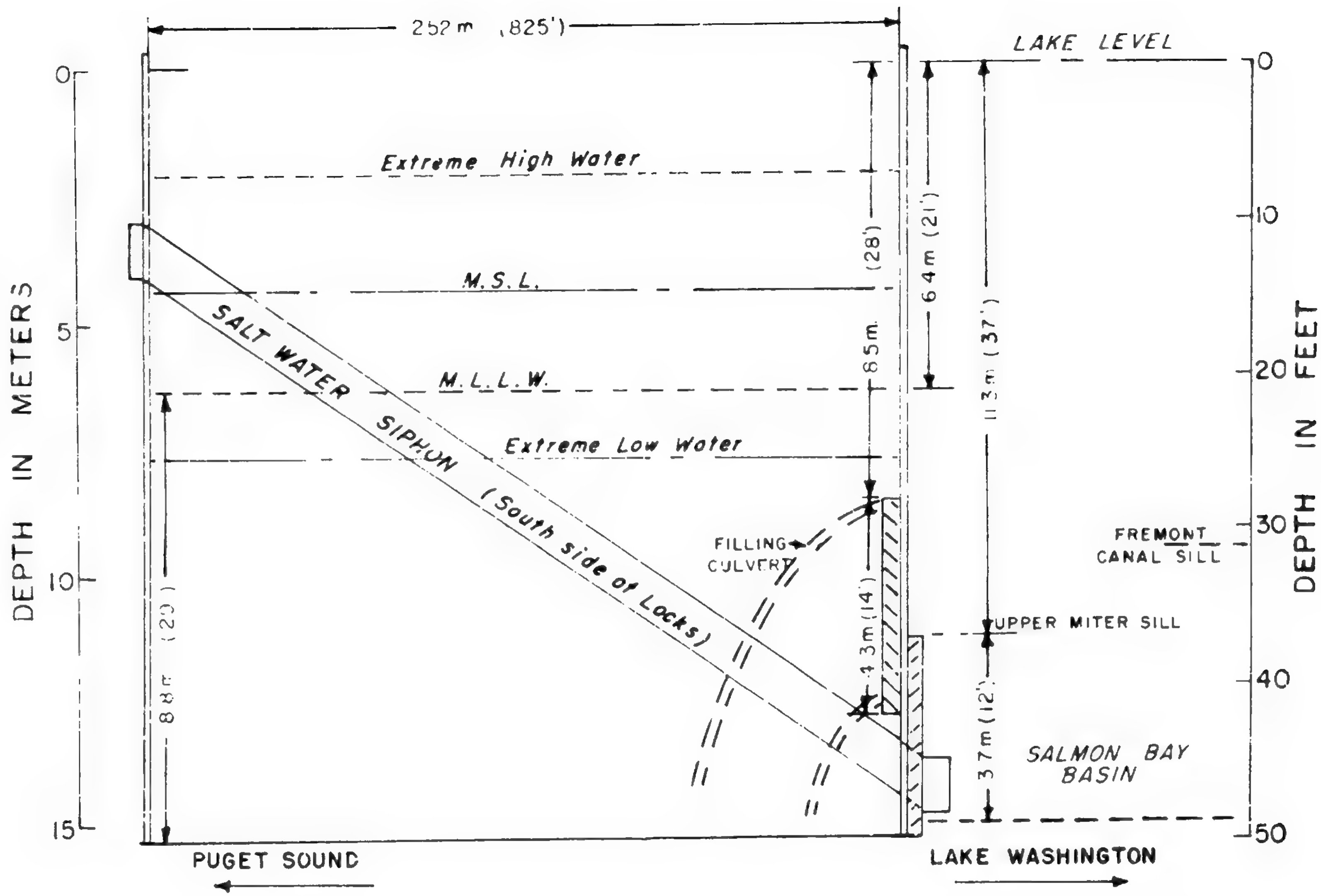


FIGURE 4. Diagram of the Large Lock Showing the Depth of the Filling Culvert and Upper Miter Sill in Relation to Lake Level and the Various Sea Levels.

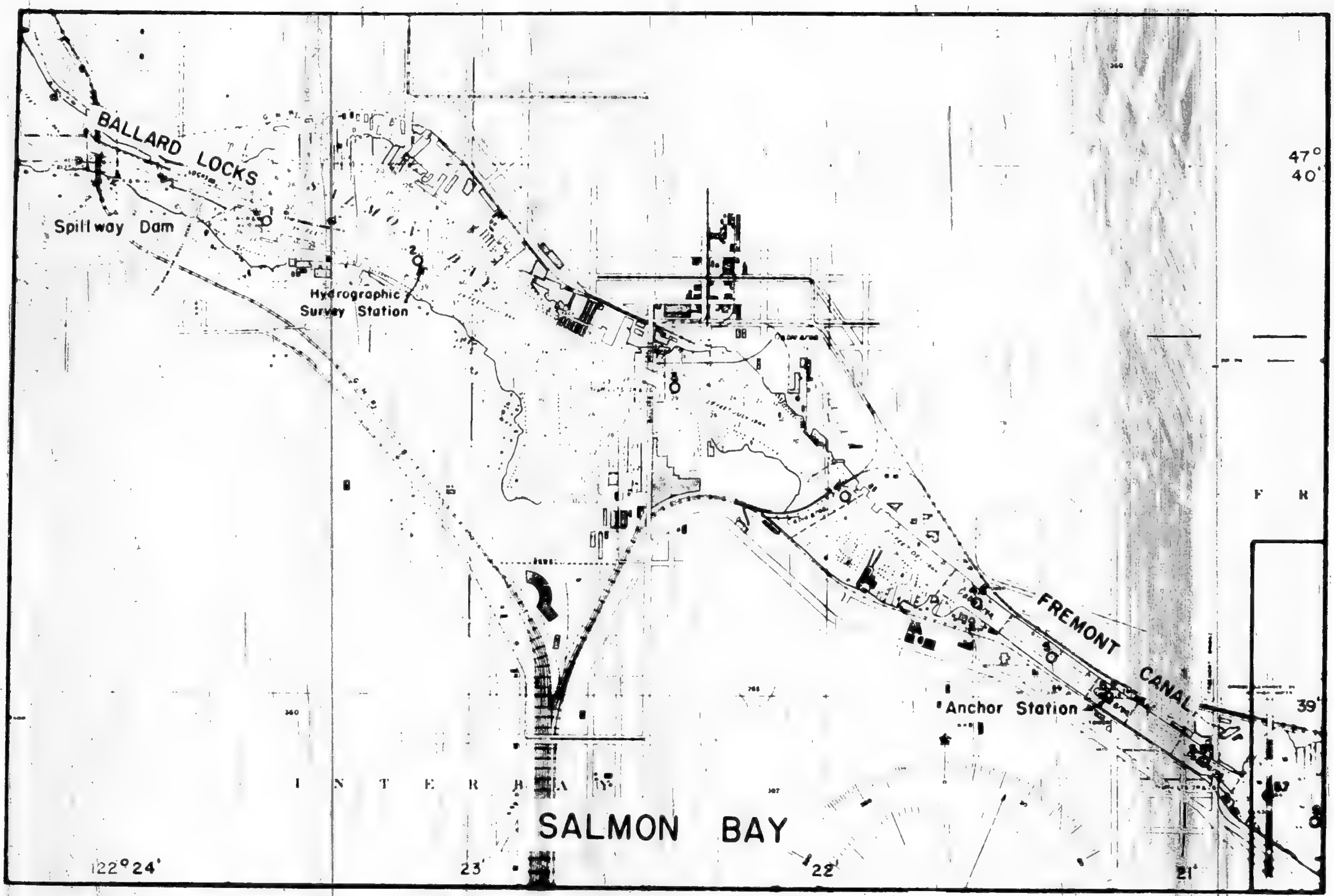


FIGURE 5. Ballard Locks to Lake Union Showing Survey Stations 1 to 6.
(Base Chart U. S. C. & G. S. Chart 6447)

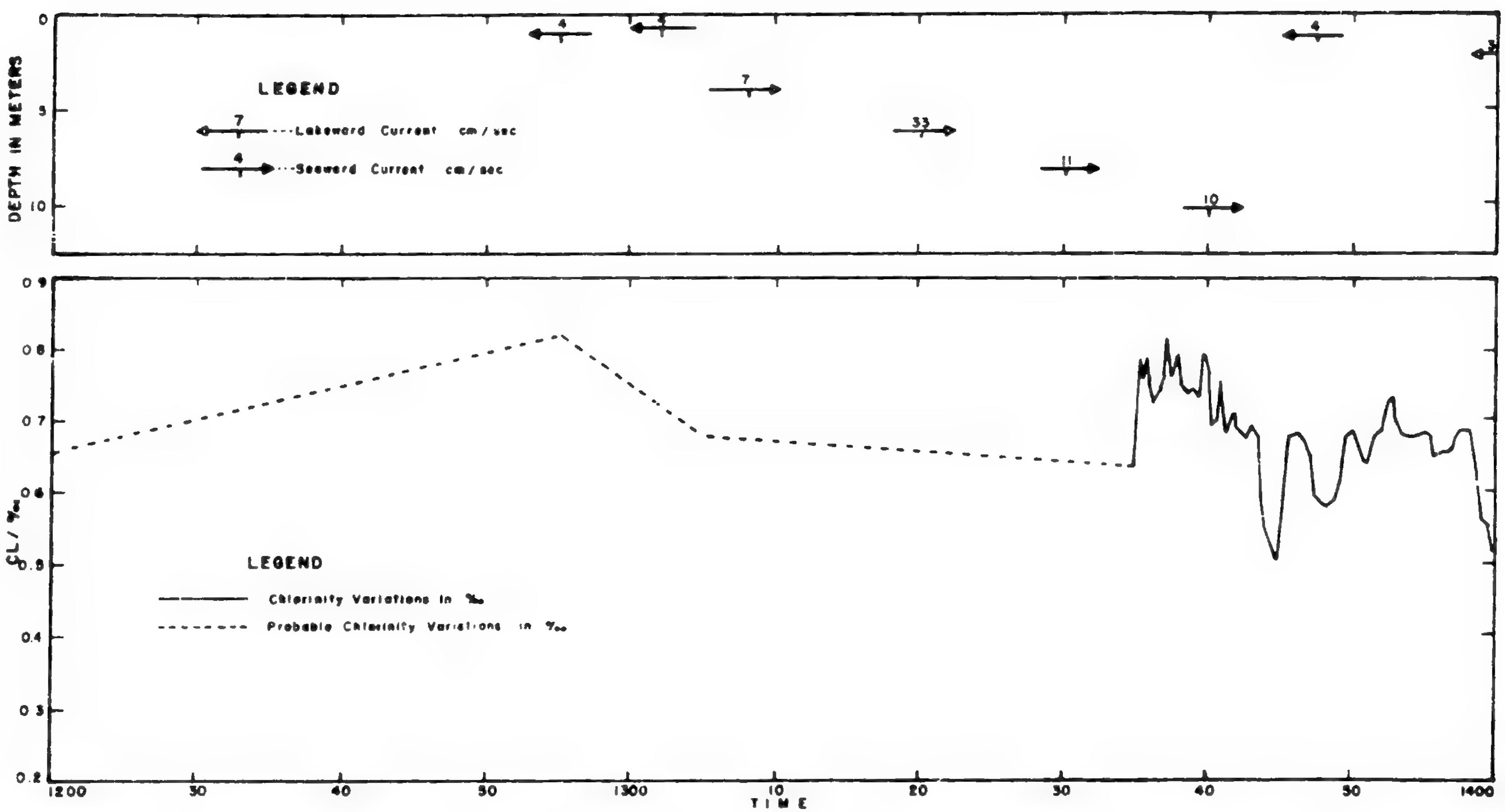


FIGURE 6a. Continuous Chlorinity ($^{0}/oo$) Variation at 8 m. and Current Velocities (cm./sec.) at Different Times and Depths in Fremont Canal 1200-1400 (zone +8 time) 16 July 1953.

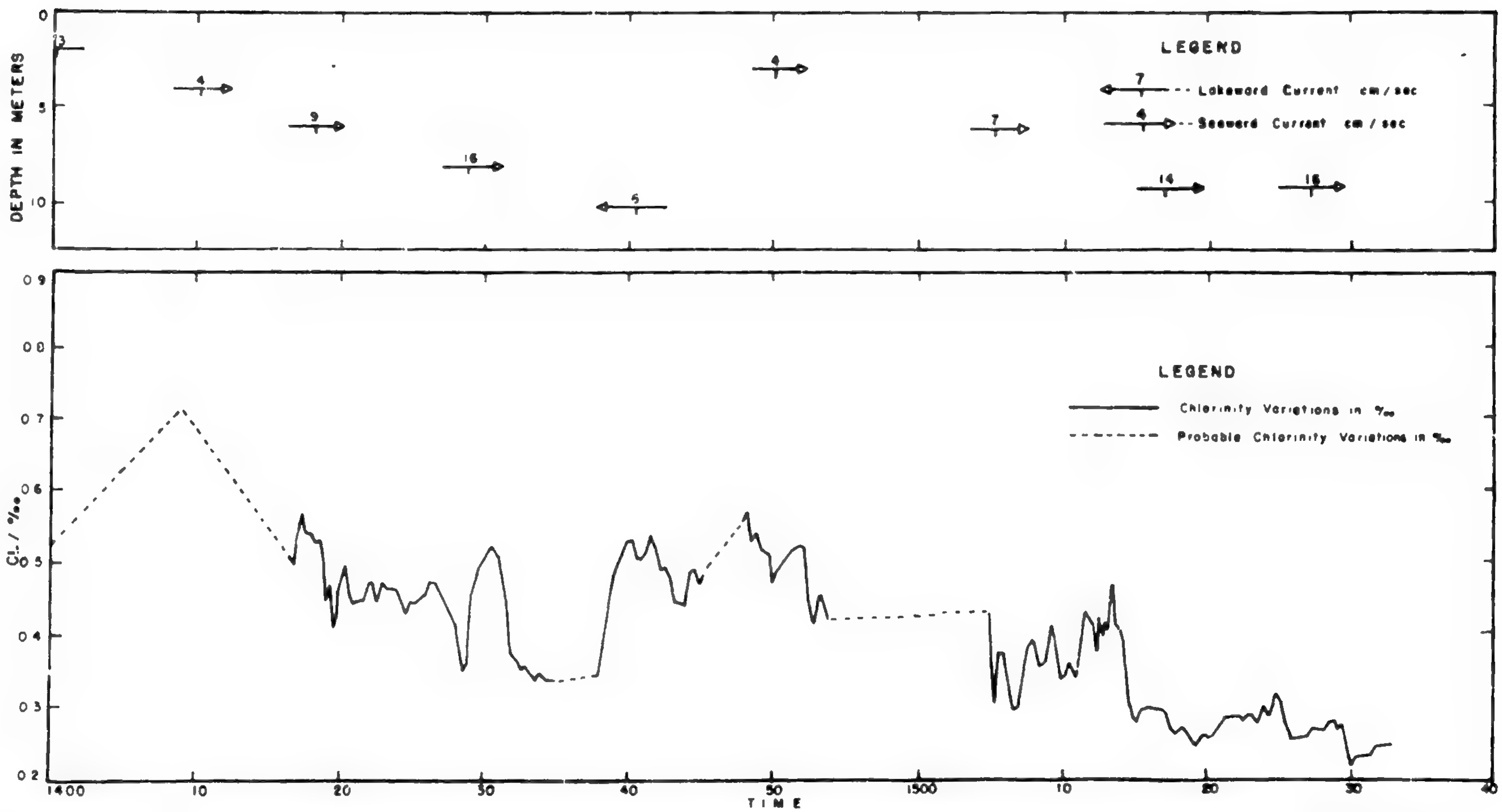


FIGURE 6b. Continuous Chlorinity (°/oo) Variation at 8 m. and Current Velocities (cm./sec.) at Different Times and Depths in Fremont Canal 1400-1540 (zone +8 time) 16 July 1953.

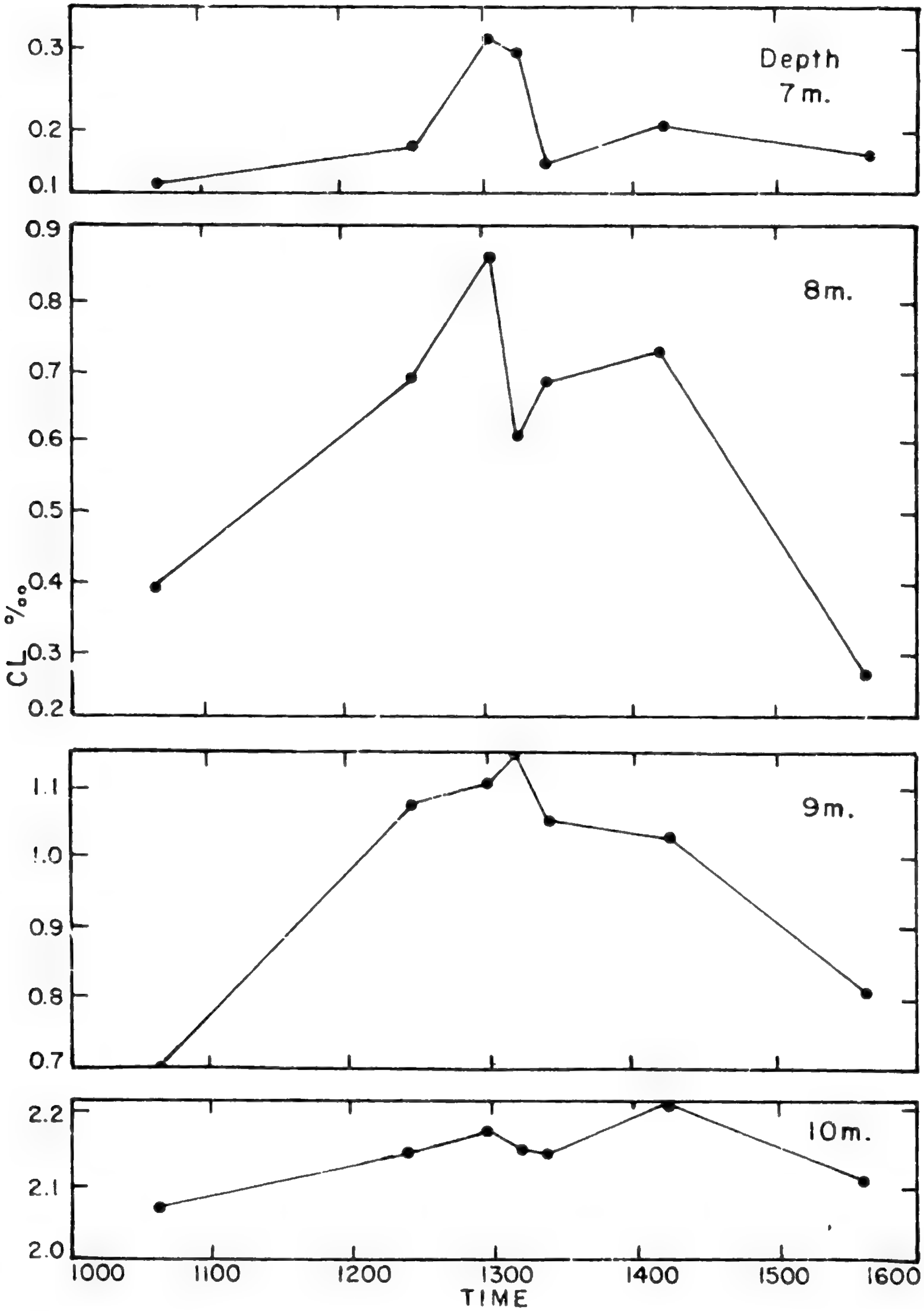


FIGURE 7. Chlorinity (°/oo) at Various Depths and Times in Fremont Canal 16 July 1953, Station 5.2.

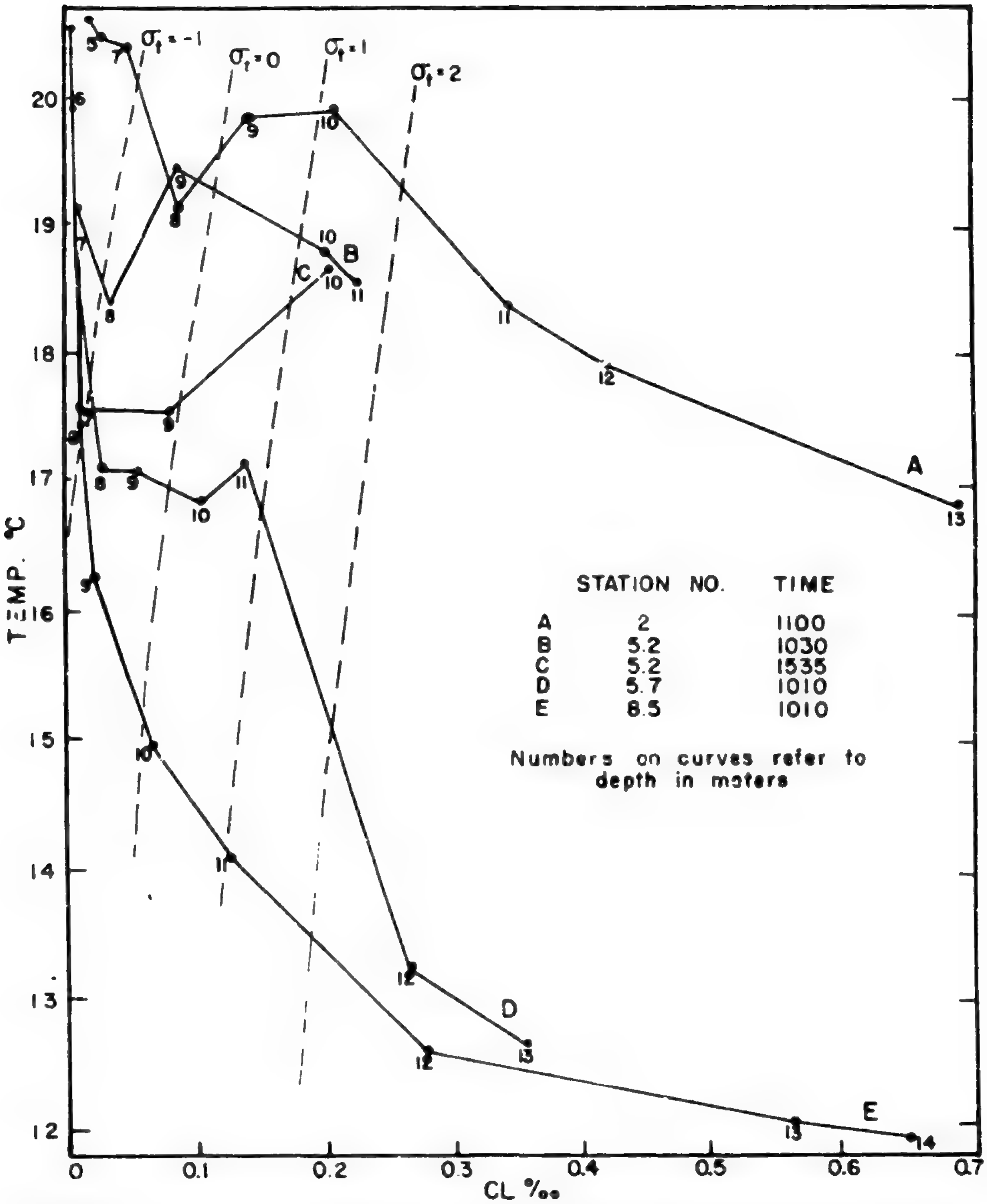


FIGURE 8. Temperature-Chlorinity Diagram Indicating the Source Water in Fremont Canal 16 July 1953.

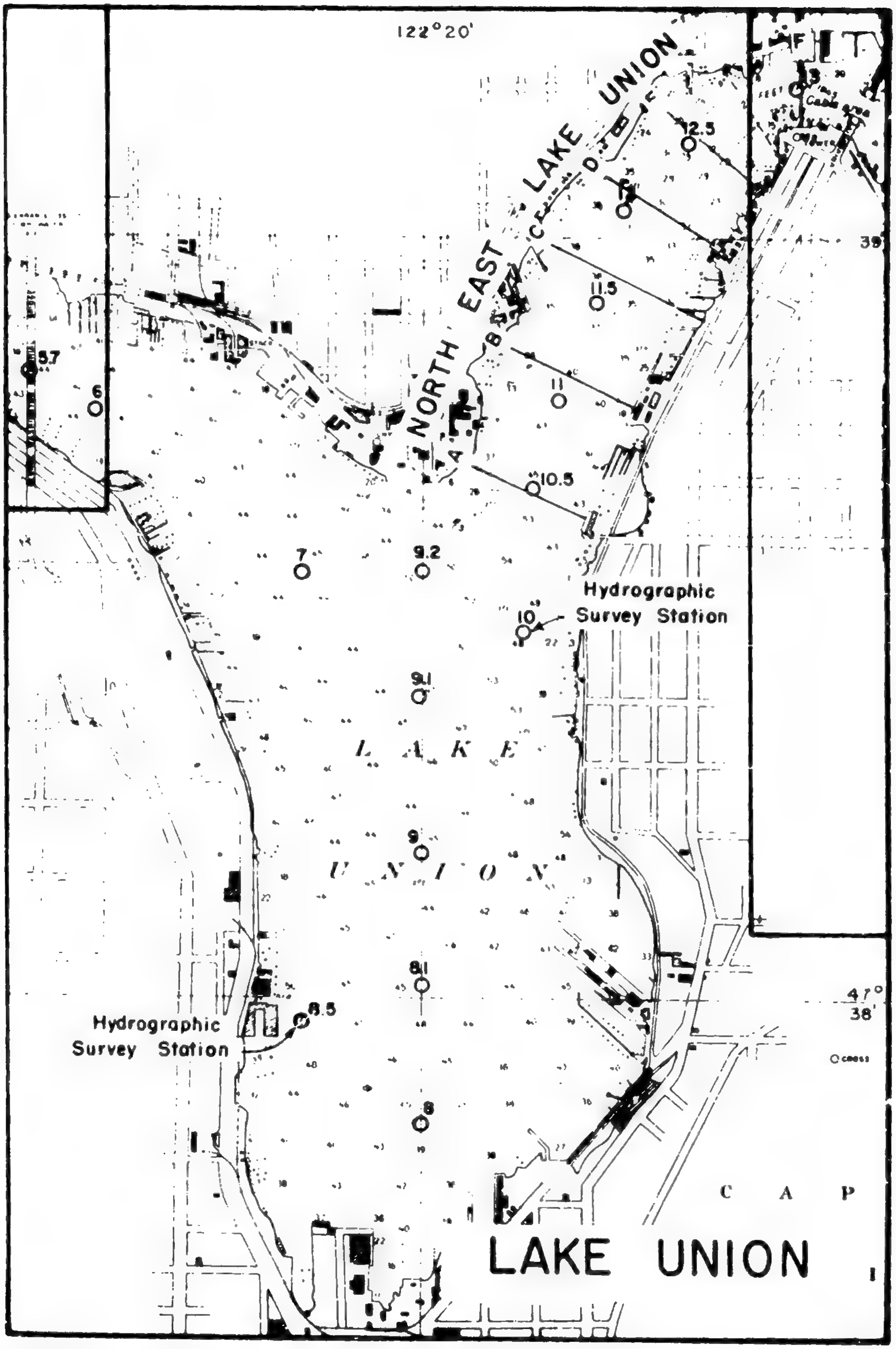


FIGURE 9. Lake Union Showing Survey Stations 6 to 13 and Indicating Locations of Cross Sectional Areas A to F of the Northeast Branch of Lake Union. (Base Chart U.S.C.&G.S. Chart 6447)

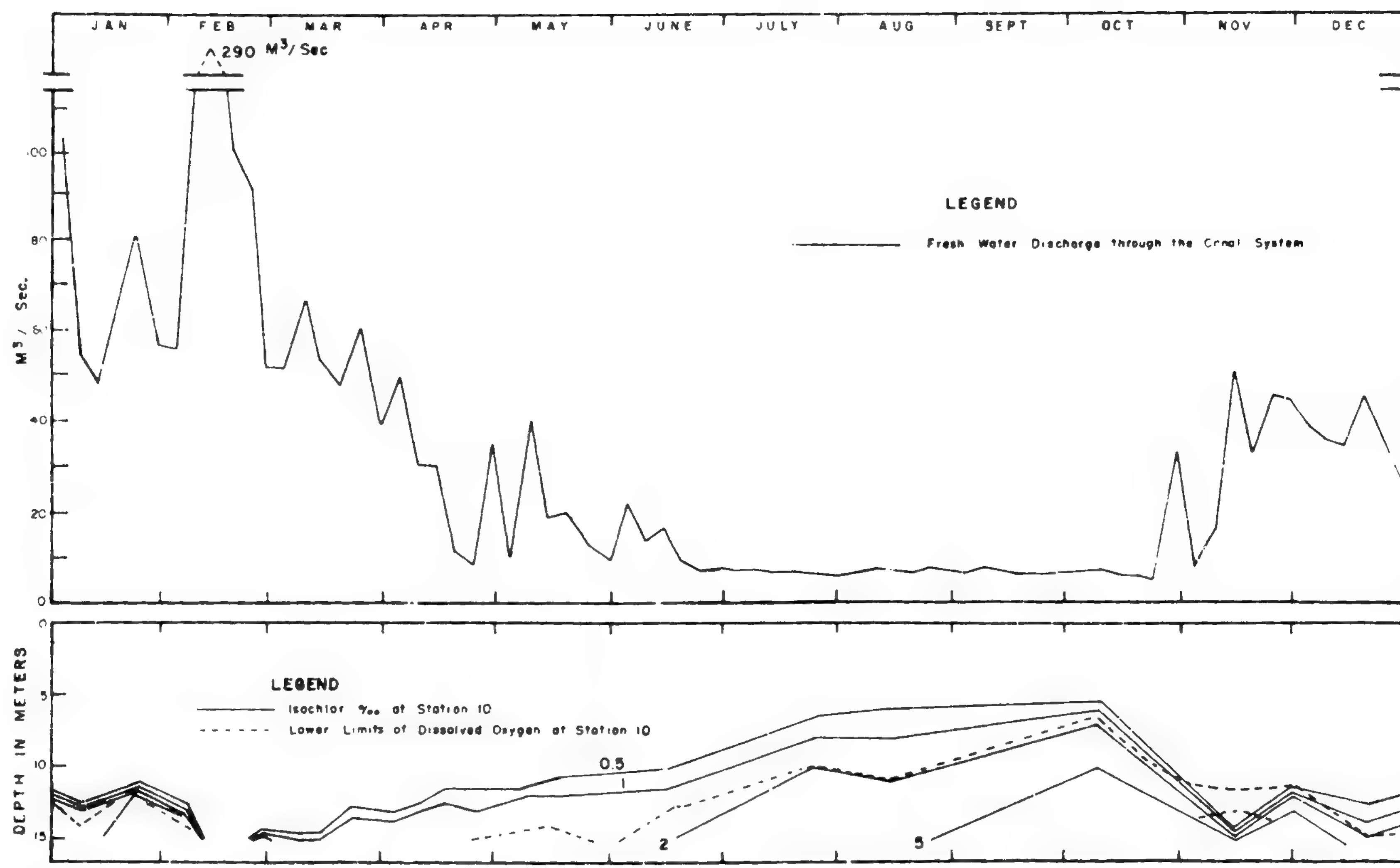


FIGURE 10a. Chlori...ty (°/oo) Variation at Station 10 in Lake Union and Fresh-Water Discharge (m.³/sec.) Through the Canal 1951.

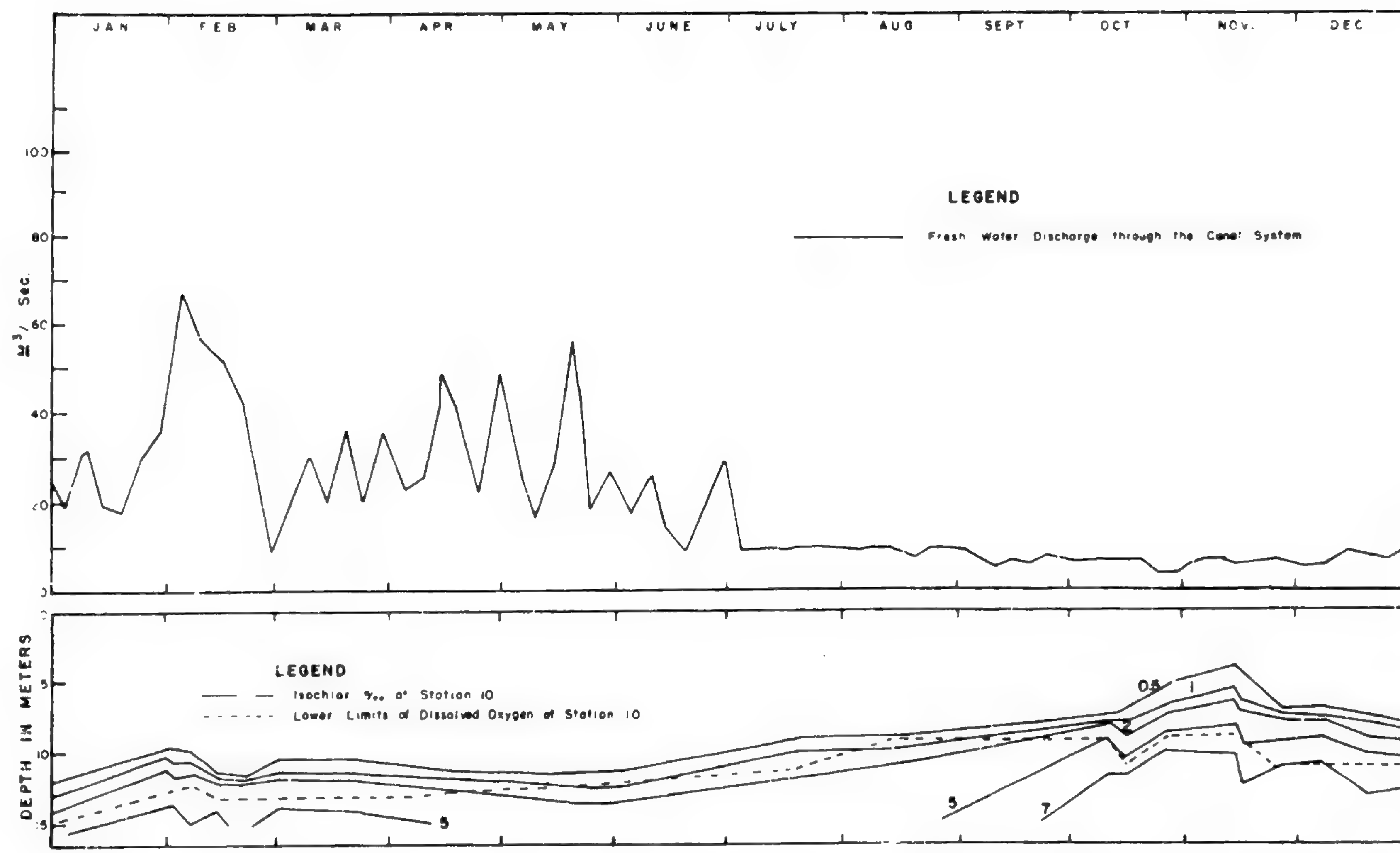


FIGURE 10b. Chlorinity (°/oo) Variation at Station 10 in Lake Union and Fresh-Water Discharge (m.^{3}/sec.) Through the Canal 1952.

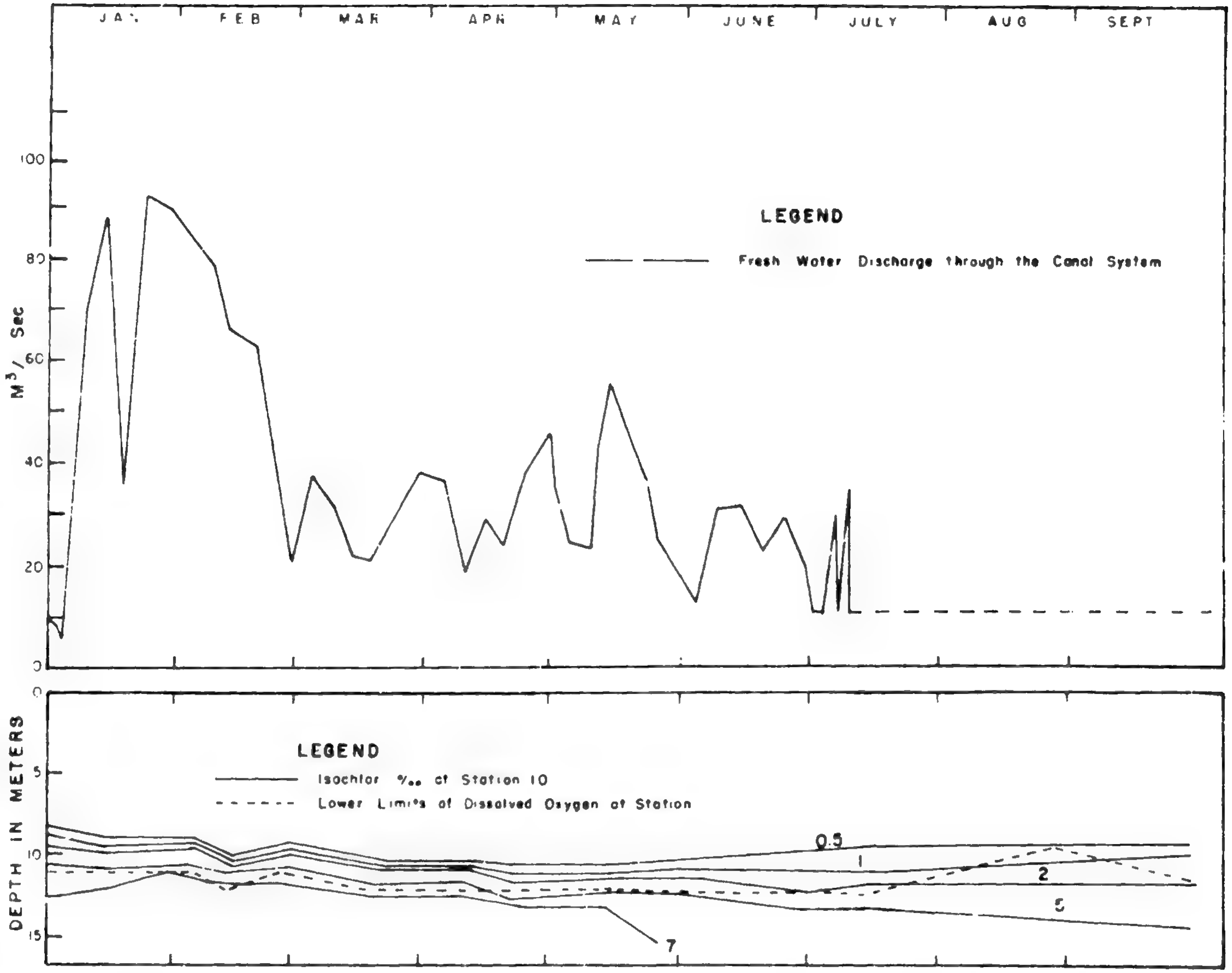


FIGURE 10c. Chlorinity ($^{o}/_{oo}$) Variation at Station 10 in Lake Union and Fresh-Water Discharge (m.^{3}/sec.) Through the Canal 1953.

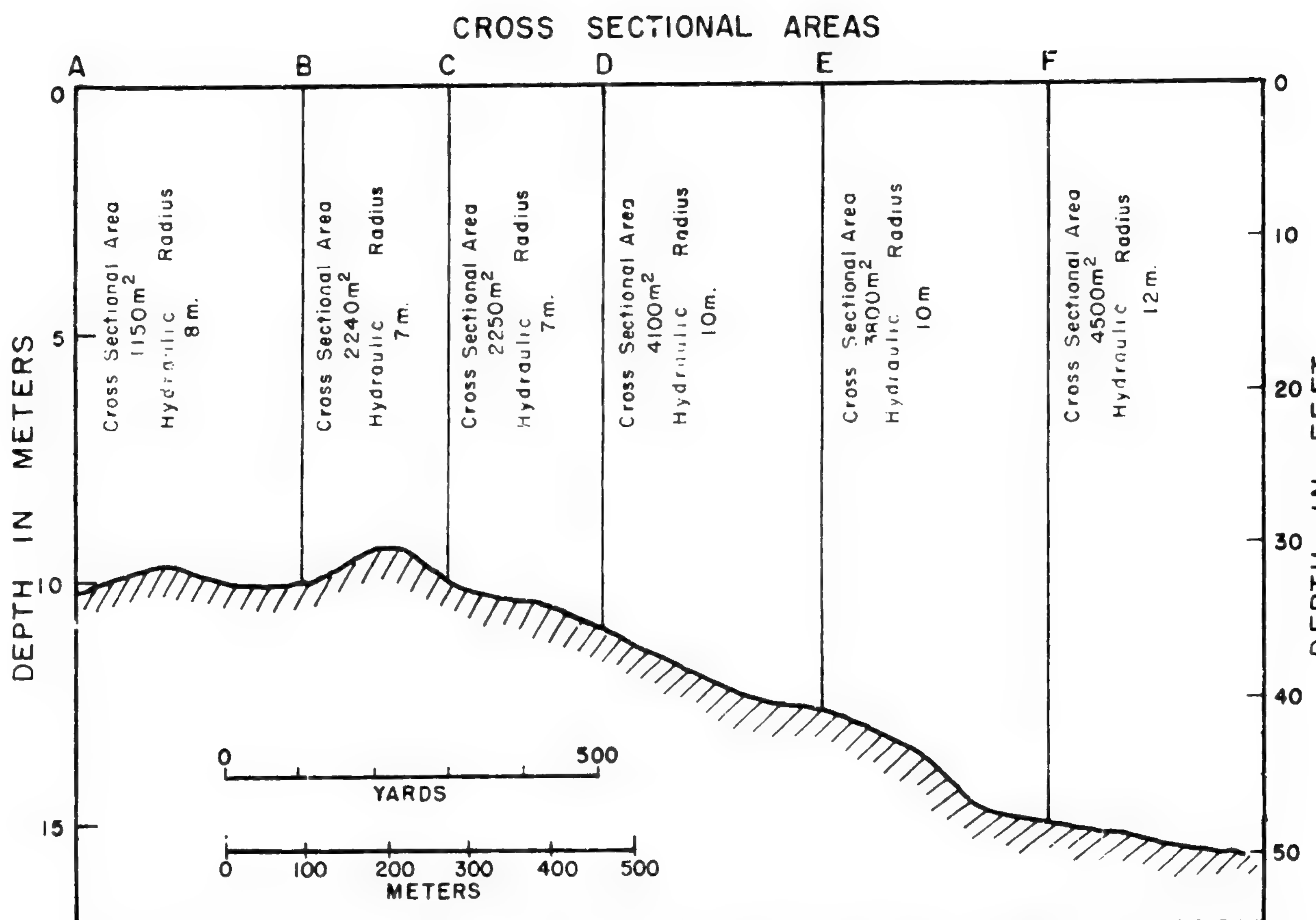


FIGURE 11. Profile of the Northeast Branch of Lake Union Giving Cross Sectional Areas (m^2).

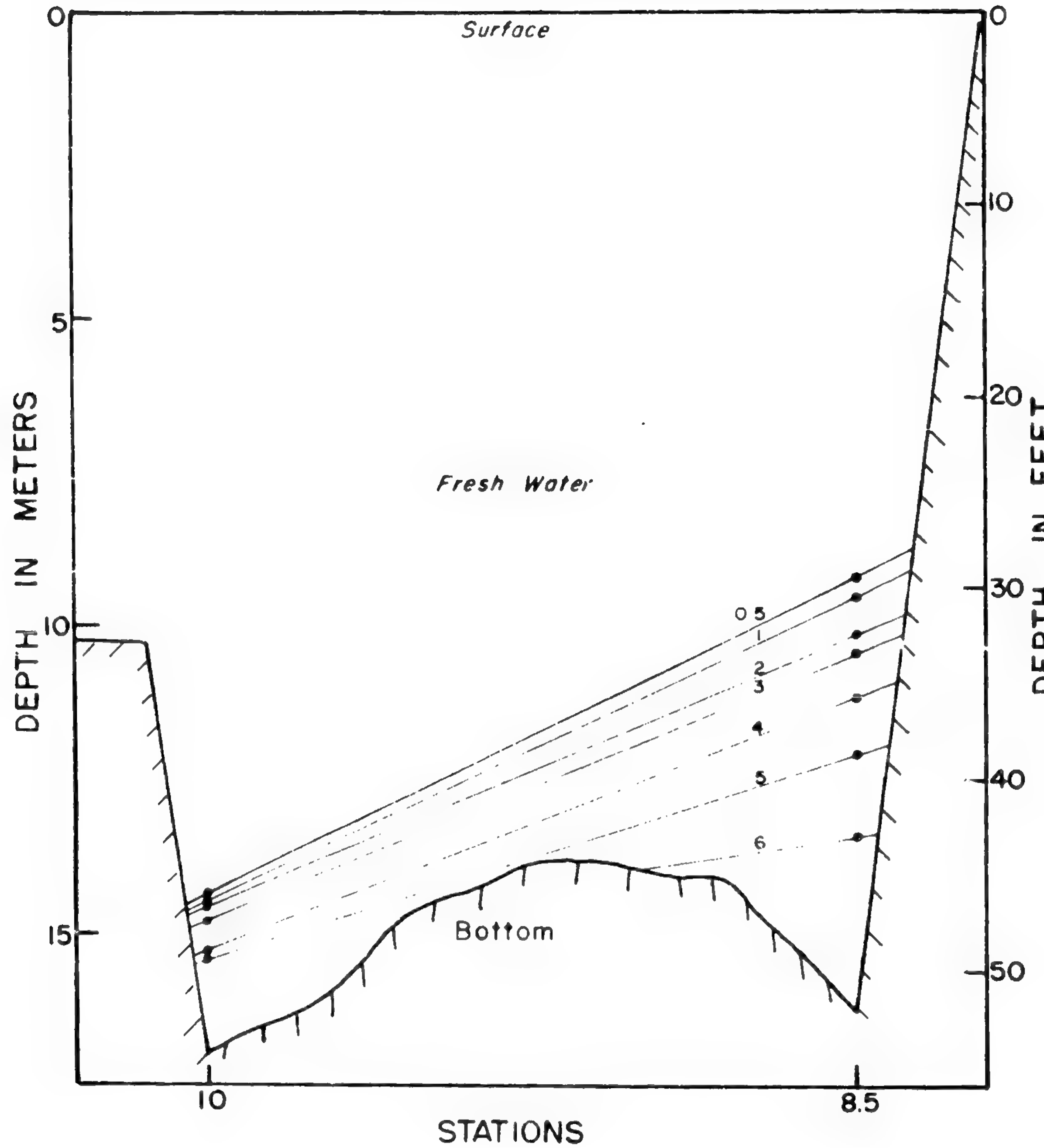


FIGURE 12. Sloping Isochlors (°/oo) in Lake Union Between Station 10 and Station 8.5 14 November 1951.

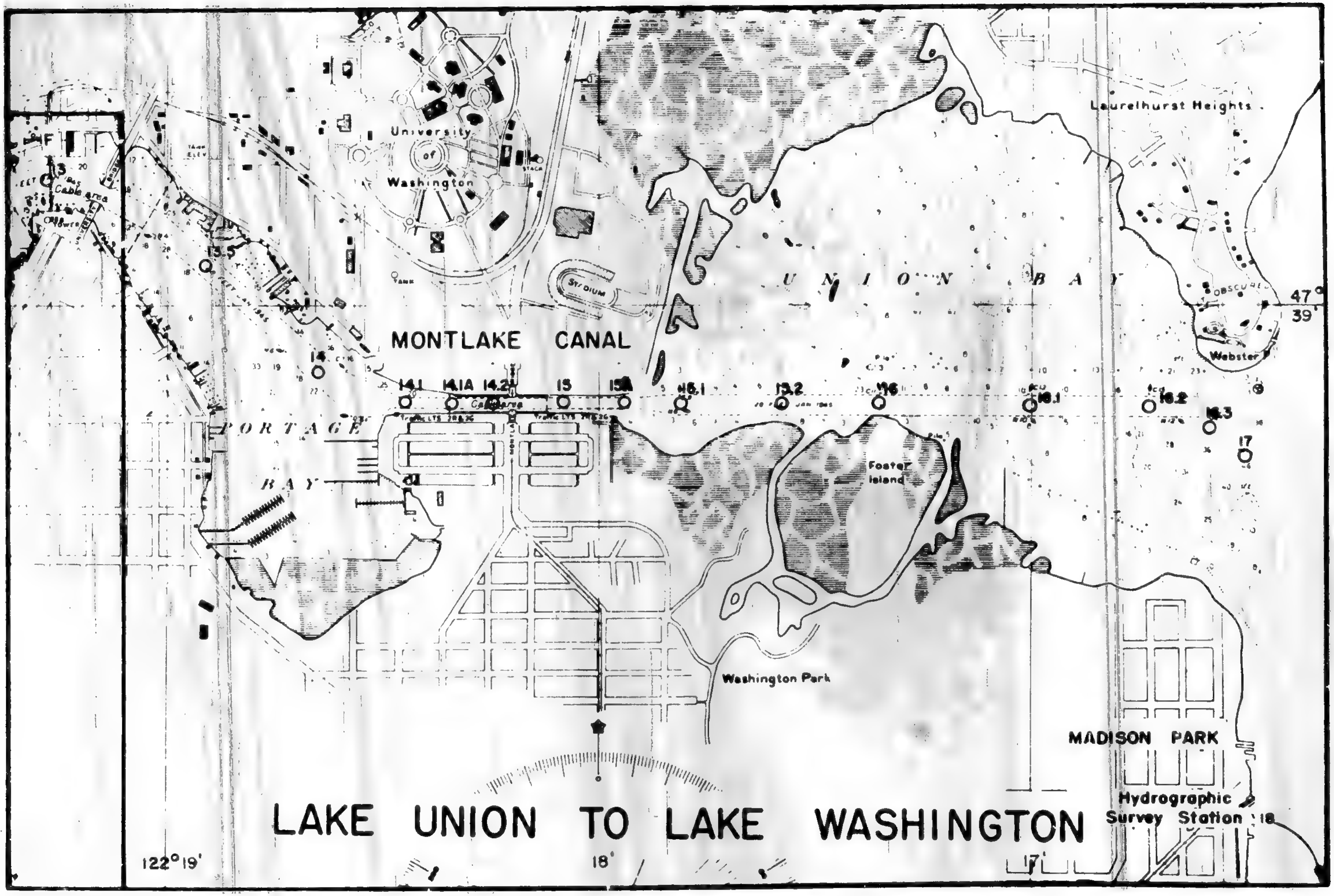


FIGURE 13. Lake Union to Lake Washington Showing Survey Stations 13 to 18.
(Base Chart U. S. C. & G. S. Chart 6447)

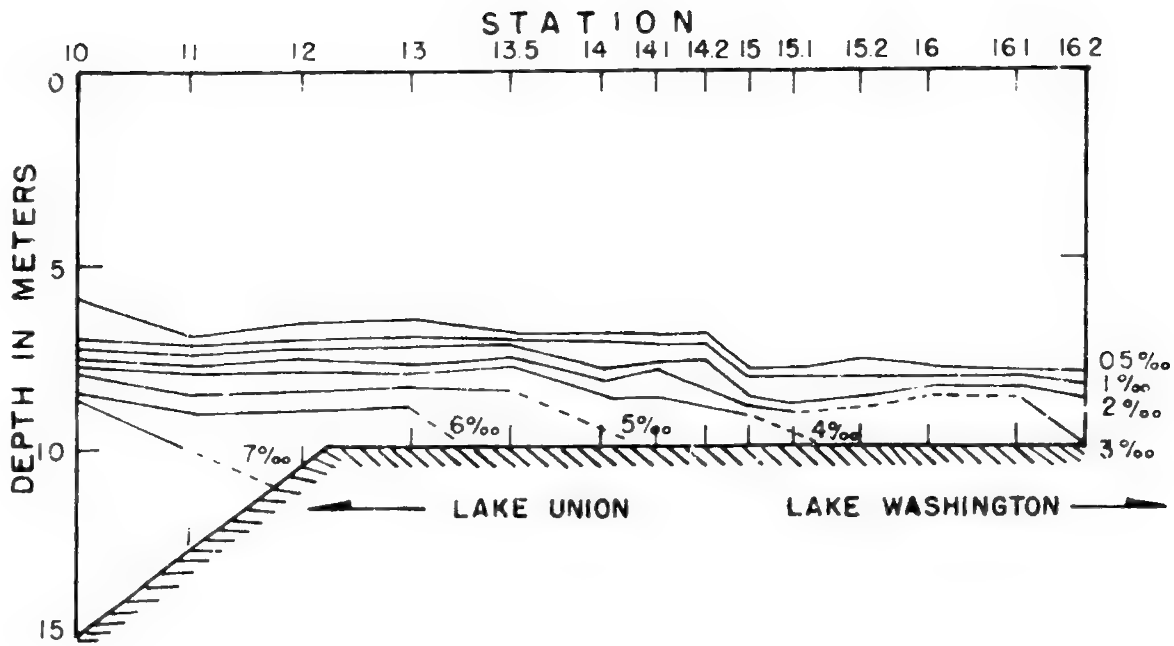


FIGURE 14. Chlorinity (°/oo) Profile from Lake Union to Lake Washington 30 October 1952.

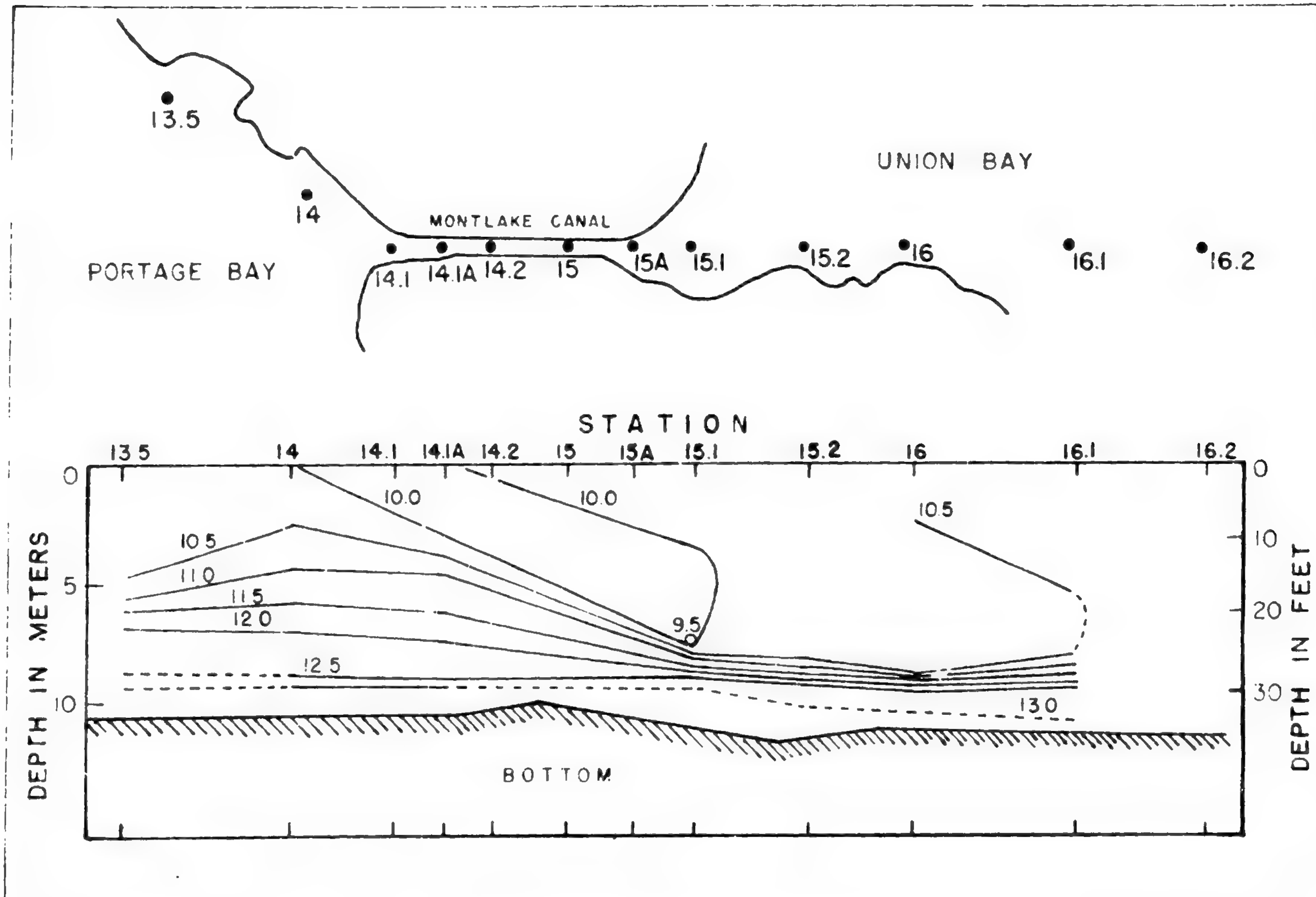


FIGURE 15. Temperature (° C.) Profile of Montlake Canal (Stations 13.5 to 16.1)
21 November 1952.

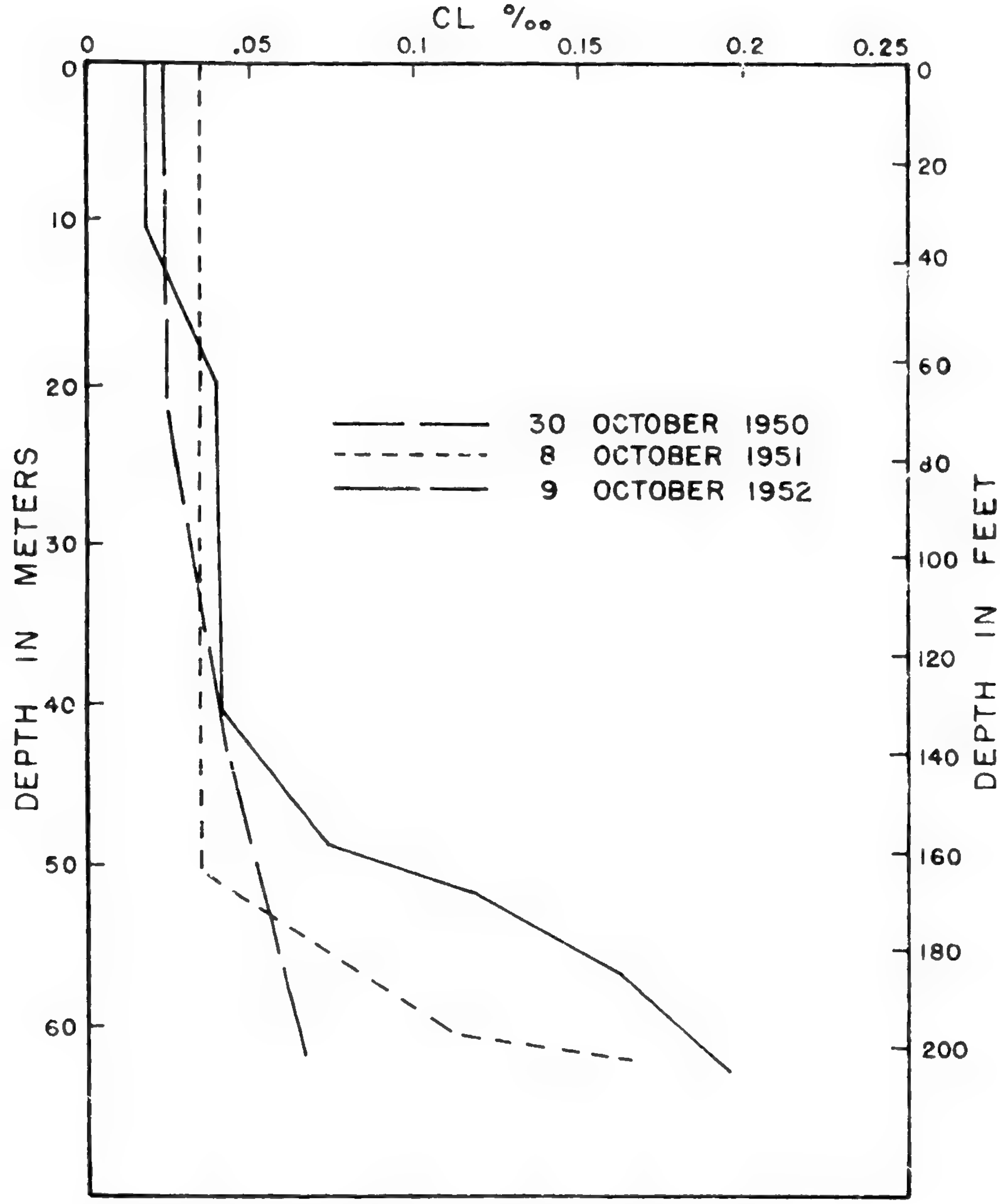


FIGURE 16. Chlorinities (°/oo) in Lake Washington (Station 18) 30 October 1950, 8 October 1951, 9 October 1952.

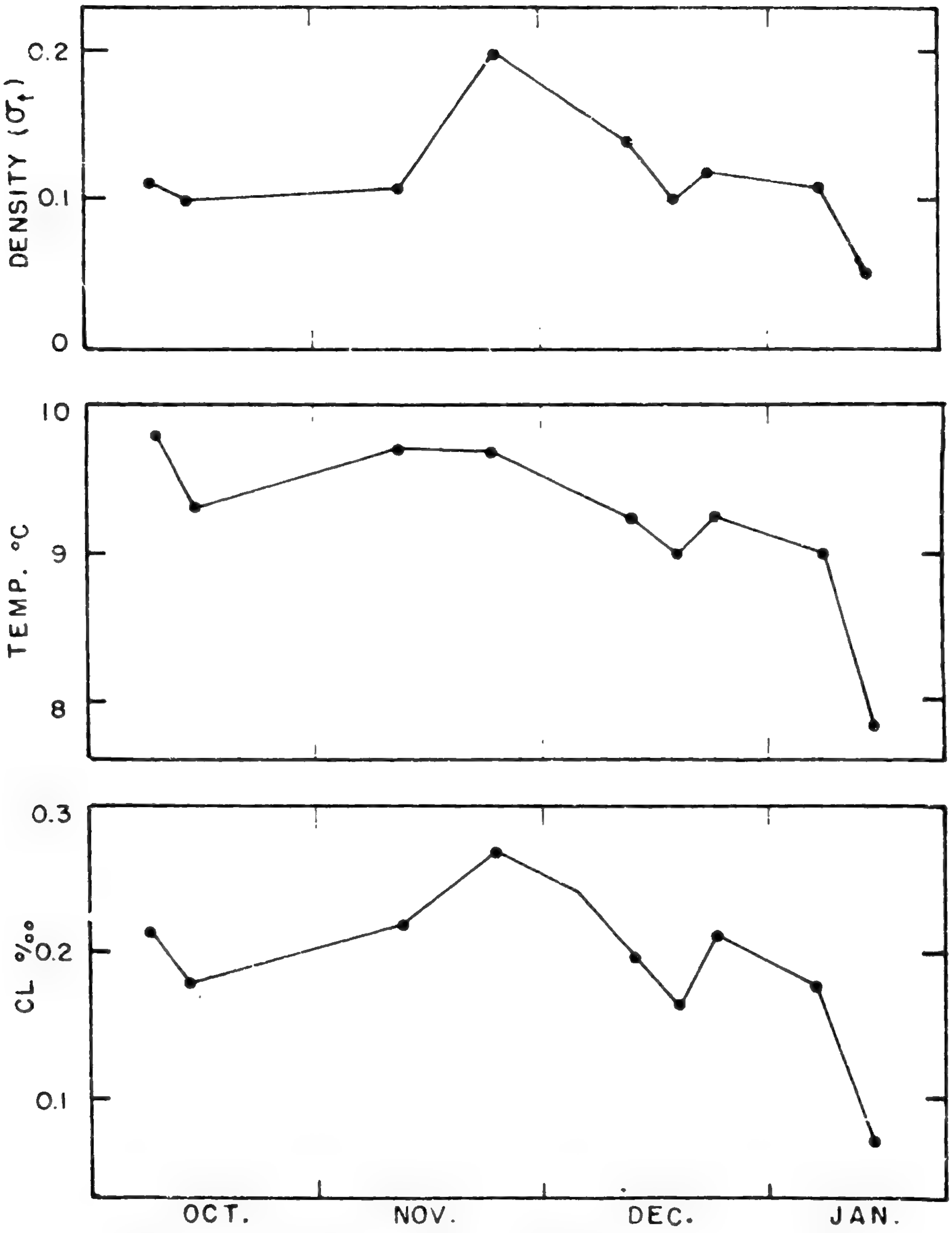


FIGURE 17. Chlorinity (°/oo), Temperature (° C.), and Density (σ_t) Variation at 60 m. (Stati.. 18) October 1952 to January 1953.

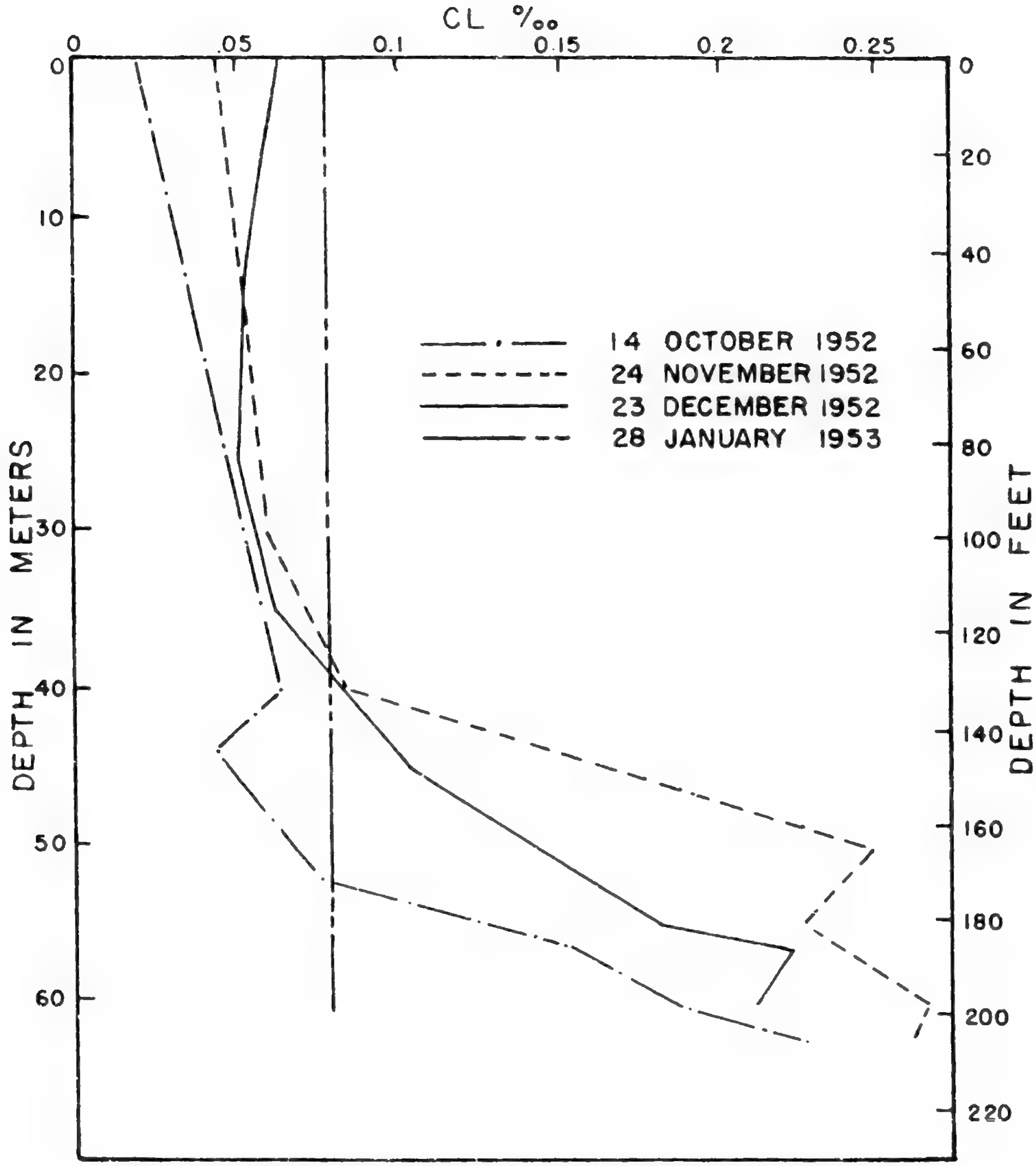


FIGURE 18. Chlorinities (°/oo) in Lake Washington (Station 18) 14 October, 24 November, 23 December 1952, 28 January 1953.

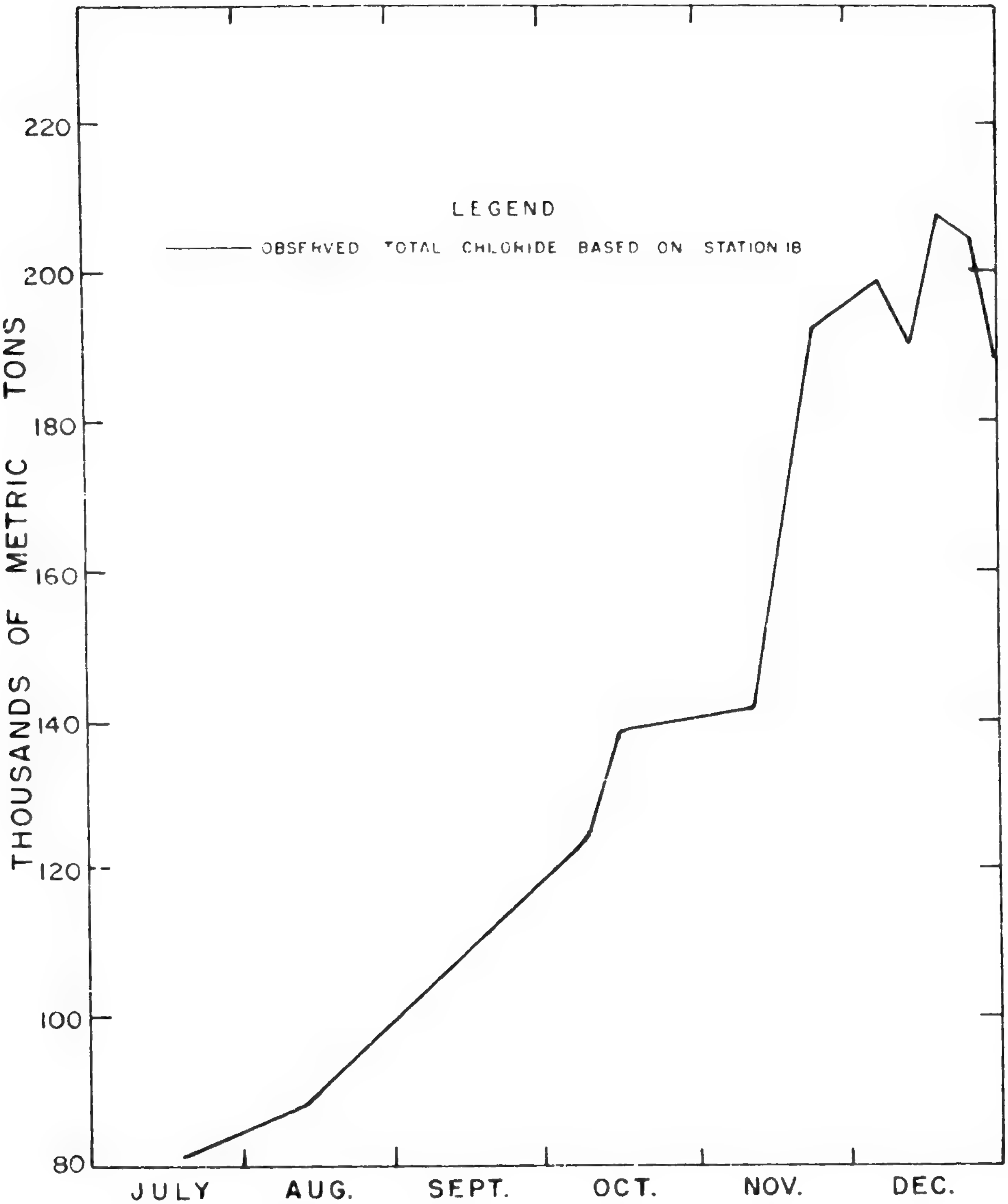


FIGURE 19a. Total Chloride (metric tons) in Lake Washington (Station 18) 1952.

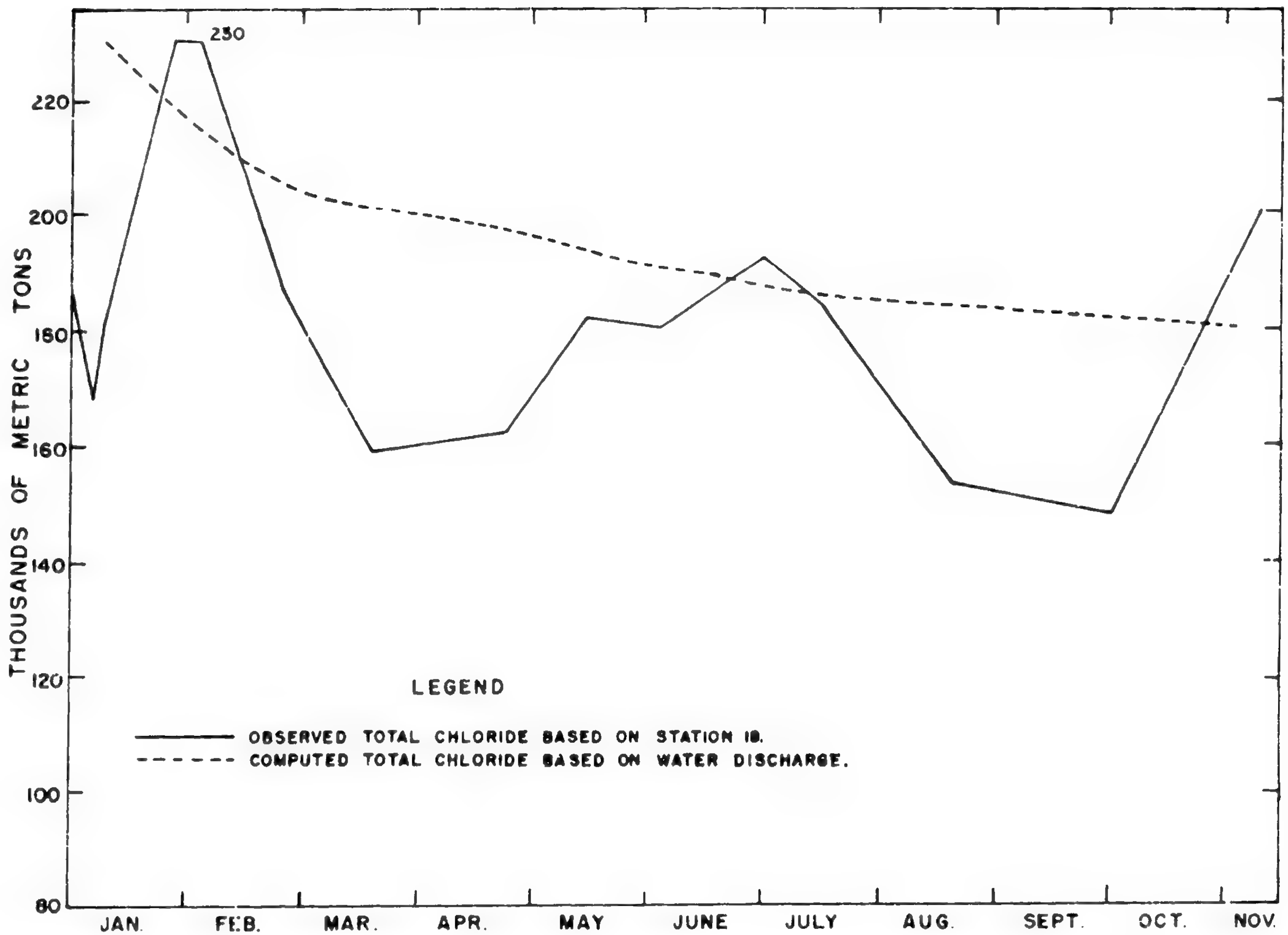


FIGURE 19b. Total Chloride (metric tons) in Lake Washington (Station 18) 1953.

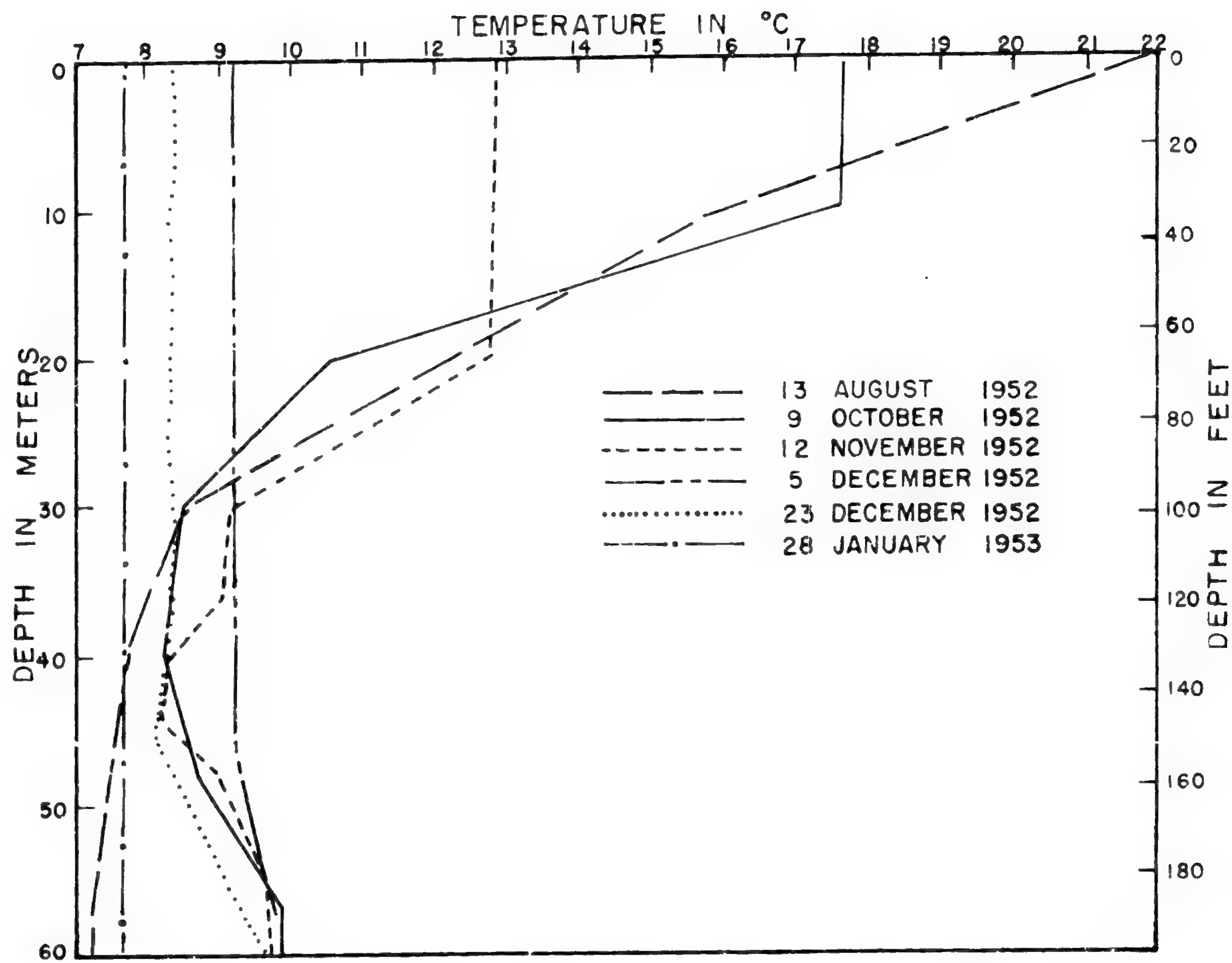


FIGURE 20. Temperatures (° C.) in Lake Washington (Station 18) Autumn 1952.

APPENDIX A

1. BALIARD LOCK LIMENSIONS

			(m.)	(ft.)
Lake datum above m.l.l.w.			6.4	21
Depth on upper miter sill		Large Lock	11.3	37
		Small Lock	5.2	17
Depth on lower miter sill		Large Lock	15.2	50
		Small Lock	11.3	37
Length of chamber between upper and lower miter sills				
	Large Lock	Full Chamber	252	825
		Upper Chamber	137	450
		Lower Chamber	115	375
	Small Lock		45.7	150
Width of chamber		Large Lock	24.4	80
		Small Lock	9.1	30

2. VOLUME OF LAKE WASHINGTON

	DEPTH INTERVAL m.	VOLUME 10^7 m.^{3}
	0-10	82
	10-20	69
	20-30	58
	30-40	44
	40-50	30
	50-60	14
	60-66	2
TOTAL		299

3. CROSS-SECTIONAL AREA* OF
FREMONT AND MONTLAKE CANALS

STATION 5.2		STATION 14.1		STATION 14.2		STATION 15A		STATION 15.1	
DEPTH INTERVAL m.	AREA m.^{2}	DEPTH INTERVAL m.	AREA m.^{2}	DEPTH INTERVAL m.	AREA m.^{2}	DEPTH INTERVAL m.	AREA m.^{2}	DEPTH INTERVAL m.	AREA m.^{2}
0-1	77	0-1	77	0-1	45	0-1	88	0-3	546
1-2	66	1-2	72	1-2	43	1-2	80	3-4	94
2-3	61	2-3	66	2-3	41	2-3	70	4-5	87
3-4	57	3-4	61	3-4	39	3-4	64	5-6	78
4-5	53	4-5	56	4-5	37	4-5	58	6-7	68
5-6	50	5-6	51	5-6	35	5-6	52	7-8	60
6-7	46	6-7	45	6-7	33	6-7	47	8-9	50
7-8	42	7-8	39	7-8	30	7-8	42	9-9.5	32
8-9	37	8-9	34	8-9	26	8-9	37		
9-10	30	9-9.5	16	9-9.5	12	9-9.5	17		
10-10.7	13								
TOTAL	532		517		341		555		1015

* Based on ship canal soundings obtained from the Corps of Engineers, Seattle, Washington.

APPENDIX B

BATHYTHERMOGRAPH TEMPERATURES
LAKE UNION TO LAKE WASHINGTON
1952

DATE	STA.	TIME	DEPTH m.	TEMP. °C.
5 Nov.	14	1230	0	13.2
			4.6	13.2
			6.2	14.1
			9.3	15.1
			10.2	15.4
	14.1	1610	0.3	13.3
			3.3	13.3
			4.6	13.4
			7.7	14.5
			8.9	14.8
			10.5	15.1
	14.2	1550	0	13.3
			4.6	13.3
			6.2	13.9
			8.0	14.4
			9.6	15.1
	15	1600	0.3	13.4
			4.0	13.2
			4.9	13.2
			6.2	13.5
			9.3	15.0
			10.2	15.1
	15.1	1605	0	13.4
			3.4	13.3
			4.0	13.1
			7.7	13.0
			9.3	15.0
			10.2	15.0

DATE	STA.	TIME	DEPTH m.	TEMP. °C.
14 Nov.	10	1450	0	12.4
			2.8	12.4
			7.1	12.9
			8.0	13.7
			9.3	15.9
			11.4	15.0
			12.3	14.1
			14.2	14.4
			14.8	14.4
	11	1525	0	12.1
			3.4	12.1
			5.2	12.2
			6.8	12.4
			7.7	13.3
			8.0	13.4
			8.9	15.5
			9.9	15.5
			11.4	14.7
			12.3	14.7
	12	1528	0	11.8
			7.1	12.0
			8.9	14.8
			10.5	15.3
	13	1532	0	11.5
			4.9	11.5
			7.1	11.9
			8.0	14.2
			8.6	15.1
			9.9	15.2

DATE	STA.	TIME	DEPTH m.	TEMP. ° C.
14 Nov.	14	1537	0	11.2
			3.3	11.2
			6.8	11.6
			7.7	12.8
			9.3	14.2
			10.5	14.6
	14.1	1540	0	11.1
			6.8	11.5
			8.3	13.1
			9.6	14.1
			10.5	14.1
	14.2	1542	0	11.1
			4.3	11.1
			5.6	11.5
			7.7	12.0
			8.9	13.5
			10.5	13.5
	15	1545	0	11.1
			4.6	11.1
			7.1	12.1
			8.9	13.7
			9.9	13.9
	15.1	1547	0	11.2
			8.0	11.2
			9.9	13.7
			10.8	13.8
	15.2	1550	0	11.4
			7.7	11.4
			9.9	13.6
			11.4	13.9
	16	1554	0	11.4
			6.8	11.3
			8.6	11.5
			9.6	13.5
			10.8	13.6
14 Nov.	16.2	1558	0	11.6
			8.6	11.6
			8.9	13.6
			10.8	13.8
	17	1600	0	11.7
			10.5	11.7
21 Nov.	13.5	1115	0	10.3
			3.7	10.3
			5.2	10.7
			6.2	11.7
			6.5	11.8
			7.4	12.4
			8.6	12.4
	14	1125	0	10.0
			3.3	10.6
			6.8	12.0
			8.6	12.4
			9.9	13.7
			10.8	13.8
	14.1	1205	0	10.0
			3.3	10.0
			4.3	11.1
			5.9	11.5
			6.5	11.8
			8.9	12.6
			9.6	13.5
			10.2	13.5
		1255	0	10.0
			3.4	10.0
			4.3	10.8
			7.4	12.0
			8.9	12.5
			9.6	13.3
			10.5	13.3

DATE	STA.	TIME	DEPTH m.	TEMP. °C.
21 Nov.	14.1	1615	0	10.1
			3.3	10.0
			4.3	10.9
			5.9	11.2
			7.4	12.2
			8.9	12.4
			9.6	13.4
	15.1	1310	0	10.3
			7.4	9.8
			8.9	12.5
			9.3	12.5
		1400	0	10.3
			2.8	10.3
			4.6	9.7
			6.8	9.5
			7.7	9.5
			8.9	12.5
			9.3	12.5
		1405	0	10.2
			3.3	10.2
			4.3	9.8
			7.4	9.6
			8.6	12.2
			9.3	12.2
	15.2	1500	0	10.4
			6.2	10.4
			8.0	10.3
			9.6	13.0
			11.1	13.1
	16	1455	0	10.5
			2.5	10.5
			4.6	10.2
			8.6	10.2
			9.6	12.7
			10.2	13.0
21 Nov.	16.1	1440	0	10.9
			4.6	10.6
			7.7	10.3
			9.6	13.0
			11.1	13.1
5 Dec.	10	1400	0	8.9
			6.8	9.3
			8.0	10.0
			10.2	14.5
			13.3	9.0
			15.1	9.0
	11	1545	0	8.5
			5.9	8.5
			8.0	9.5
			10.5	14.4
			11.7	13.3
			13.0	13.3
	12	1510	0	8.3
			6.5	8.4
			7.7	9.5
			9.3	11.8
			9.6	12.0
	13	1555	0	8.4
			5.9	8.4
			7.1	8.5
			9.9	13.6
			10.5	13.6
	14	1600	0	8.4
			5.9	8.4
			8.3	9.5
			9.6	11.8
			10.5	11.8

DATE	STA.	TIME	DEPTH m.	TEMP. °C.	DATE	STA.	TIME	DEPTH m.	TEMP. °C.
5 Dec.	14.1	1205	0	8.6	5 Dec.	16	1120	0	6.0
			6.8	8.8				8.3	6.0
			8.9	9.7				9.9	10.6
			9.6	10.7				10.5	10.7
			9.7	10.7					
						16.1	1000	0	8.9
	15.1	1140	0	8.7				7.1	8.8
			7.7	8.7				8.3	8.9
			9.3	9.2				9.6	10.1
			9.6	10.4				10.2	10.3
			10.2	10.4					
						16.2	0950	0	9.0
	15.2	1130	0	8.8				8.0	9.0
			8.3	8.9				8.6	8.9
			8.9	9.1				9.9	10.7
			9.6	10.0				10.2	10.7
			10.2	10.6					
			10.8	10.6					

APPENDIX C

CONDUCTIVITY-TEMPERATURE-DEPTH RECORDER DATA

24 OCTOBER 1952

STA.	TIME	DEPTH m.	TEMP. °C.	Cl. ‰
2	1025	0	15.80	0.475
		1	15.80	0.475
		2	15.80	0.470
		3	15,80	0.475
		4	15.80	0.485
		5	15.80	0.485
		6	15.80	0.525
		7	15.90	0.700
		8	15.10	3.00
4	1040	0	15.90	0.385
		2	15.90	0.385
		3	15.90	0.400
		4	15.90	0.420
		5	16.00	0.475
		6	15.95	0.555
		7	16.00	0.710
		8	15.00	5.30
		9	14.45	7.50
		10	14.30	8.40
6	--	0	16.15	0.345
		1	16.15	0.345
		2	16.15	0.345
		3	16.15	0.345
		4	16.20	0.360
		5	16.20	0.365
		6	16.20	0.365
		7	16.00	0.980
		8	15.45	5.15
		9	15.85	6.80
		10	15.20	7.35
		11	15.05	7.25
		12	14.65	8.20
		12.5	14.60	7.75
7	1100	0	16.55	0.405
		1	16.60	0.405
		3	16.60	0.405
		5	16.60	0.405
		6	16.55	0.400
		7	16.15	1.20
		8	15.60	5.75
		9	15.85	6.75
		10	15.35	7.05
8	1215	0	16.25	0.445
		3	16.20	0.445
		5	16.40	0.530
		6	16.65	0.900
		7	16.30	1.15
		8	16.90	4.25
		9	16.35	6.40
		10	16.05	6.60
		11	15.80	7.00
		12	15.45	7.15
		12.5	15.35	7.05
9	1230	0	16.25	.395
		3	16.25	.390
		5	16.20	.380
		6	16.15	.400
		7	16.30	.685
		8	16.80	4.15
		9	16.20	6.50
		10	15.90	6.90
		11	15.70	7.20
		12	15.25	7.30
		13	15.10	7.20

24 OCTOBER 1952

STA.	TIME	DEPTH m.	TEMP. °C.	Cl. °/oo
9.6	1230	0	16.25	0.390
		3	16.25	0.390
		5	16.40	0.405
		6	16.45	0.410
		7	16.35	1.00
		8	15.80	4.25
		9	16.20	6.60
		10	15.90	6.95
		11	15.50	7.20
		12	14.85	7.70
		13	14.80	7.75
10	1120	0	16.50	0.410
		3	16.50	0.400
		5	16.45	0.400
		6	16.50	0.405
		7	16.75	1.60
		8	16.15	4.30
		9	16.15	6.85
		10	15.80	7.20
		11	15.00	7.30
		12	15.00	7.45
		13	15.00	7.85
		14	14.95	7.55
10.5	1240	0	15.70	0.245
		3	15.80	0.255
		5	16.10	0.335
		6	16.30	0.370
		7	16.35	0.425
		8	15.80	5.55
		9	16.15	6.60
		10	15.85	7.00
		11	15.10	7.15
		12	15.25	7.55
		13	15.10	7.60

STA.	TIME	DEPTH m.	TEMP. °C.	Cl. °/oo
11	1245	0	15.55	0.215
		3	15.55	0.215
		5	15.55	0.215
		6	15.90	0.290
		7	16.20	0.490
		8	15.90	5.15
		9	16.15	6.60
		10	15.90	6.80
		11	15.65	7.15
		12	15.60	6.80
11.5	1300	0	15.40	0.160
		2	15.40	0.160
		4	15.40	0.160
		5	15.50	0.200
		6	15.70	0.235
		7	15.90	0.325
		8	16.00	5.60
		9	15.95	6.70
		10	15.85	6.05
12.5	1300	0	15.35	0.150
		2	15.35	0.150
		4	15.40	0.170
		5	15.45	0.180
		6	15.55	0.210
		7	15.65	0.235
		8	16.05	6.00
		9	16.10	5.75
13	1305	0	15.35	0.130
		2	15.35	0.130
		4	15.35	0.130
		5	15.40	0.130
		6	15.35	0.145
		7	15.75	0.335
		8	16.00	5.60
		9	16.10	6.35

24 OCTOBER 1952

STA.	TIME	DEPTH m.	TEMP. °C.	Cl. ‰
13.5	1310	0	15.35	0.130
		2	15.35	0.130
		4	15.35	0.130
		5	15.35	0.125
		6	15.35	0.125
		7	15.55	0.240
		8	15.95	3.45
14	1320	0	15.40	0.095
		2	15.40	0.095
		4	15.40	0.125
		5	15.40	0.130
		6	15.45	0.175
		7	15.90	0.370
		8	16.15	1.90
		9	16.00	4.70
15	1325	0	15.35	0.070
		2	15.40	0.065
		4	15.35	0.075
		5	15.70	0.180
		6	15.75	0.210
		7	16.00	0.295
		8	16.00	0.430
		9.5	16.00	5.05
16	1330	0	15.30	0.050
		2	15.30	0.050
		4	15.15	0.050
		6	15.10	0.060
		7	15.10	0.085
		8	15.95	0.470
		9	16.05	4.50
16.5	--	0	15.20	0.050
		2	15.20	0.050
		4	15.15	0.050
		6	14.90	0.055
		7	14.80	0.060
		8	15.35	0.300
		9	16.10	2.65

STA.	TIME	DEPTH m.	TEMP. °C.	Cl. ‰
17	1345	0	15.40	0.045
		2	15.40	0.045
		4	15.35	0.045
		6	15.25	0.055
		7	15.10	0.055
		8	14.95	0.070
		9	14.90	0.070
		10	14.90	0.070
		11	15.10	0.280
		12	15.45	0.675
17.1	1400	0	15.45	0.045
		5	15.45	0.045
		10	14.95	0.050
		15	13.85	0.070
		20	13.95	0.290
		25	13.05	0.320
		26	9.50	0.200
17.2	1410	0	15.45	0.040
		5	15.50	0.040
		10	15.40	0.040
		15	13.90	0.050
		17	13.05	0.060
		18	12.65	0.060
		20	11.00	0.110
		30	8.30	0.050
		40	7.80	0.050
		45	8.75	0.150
		47	9.05	0.180
		50	9.10	0.195
		55	10.00	0.300
		60	9.75	0.300
		63	9.50	0.280

30 OCTOBER 1952

STA.	TIME	DEPTH m.	TEMP. °C.	Cl. °/oo
10	1000	0	15.20	0.395
		5	15.30	0.405
		6	15.45	0.490
		7	16.00	1.15
		8	15.90	5.05
		9	16.05	7.60
		10	15.60	6.65
		11	15.50	6.90
		12	15.10	7.25
		13	14.85	7.40
		14	14.70	6.40
11	1015	0	14.80	0.310
		5	14.70	0.310
		6	14.80	0.315
		7	15.20	0.420
		8	15.95	4.20
		9	16.05	6.70
		10	15.80	7.00
		11	15.50	7.20
		12	14.70	6.50
12	1025	0	14.15	0.170
		5	14.50	0.265
		6	14.70	0.295
		7	15.45	1.05
		8	15.70	4.45
		9	15.90	5.45
13	1030	0	14.15	0.150
		5	14.15	0.170
		6	14.60	0.260
		7	15.00	0.830
		8	15.70	4.60
		9	15.90	6.35
13.5	--	0	14.20	0.135
		5	14.15	0.155
		6	14.20	0.170
		7	14.60	0.285
		8	15.85	5.45
14	1045	0	14.25	0.115
		5	14.25	0.175
		6	14.25	0.185
		7	14.80	0.325
		8	15.55	2.20
		9	15.80	4.55
14.1	1050	0	14.25	0.145
		3	14.25	0.165
		5	14.25	0.170
		6	14.45	0.235
		7	15.05	0.370
		8	15.60	3.40
		9.5	15.80	4.85
14.2	1100	0	14.15	0.080
		3	14.15	0.100
		5	14.40	0.175
		6	14.60	0.245
		7	15.00	0.375
		8	15.45	2.60
15	1105	0	14.15	0.085
		3	14.15	0.085
		5	14.20	0.110
		6	14.50	0.205
		7	14.75	0.290
		8	15.50	2.60
		9	15.70	4.15

APPENDIX C--Continued

30 OCTOBER 1952

STA.	TIME	DEPTH m.	TEMP. °C.	Cl. °/oo
15.1	1110	0	14.15	0.060
		3	14.10	0.060
		5	14.10	0.075
		6	14.10	0.075
		7	14.10	0.080
		7.5	14.10	0.110
		8	14.60	0.385
		8.5	15.20	1.75
		9	15.25	2.40
15.2	1115	0	14.20	0.070
		6	14.10	0.075
		7	14.10	0.095
		7.5	14.55	0.200
		8	14.90	0.600
		8.5	15.30	1.70
		9	15.55	2.70
16	1120	0	14.20	0.070
		6	14.05	0.075
		7	14.10	0.095
		8	14.80	0.275
		8.5	15.40	2.10
16.1	—	0	14.35	0.065
		6	14.20	0.070
		7	14.05	0.075
		8	14.25	0.170
		8.5	15.05	0.580
		9	15.80	3.75
		9.5	15.80	3.75
		10.5	15.80	3.35
16.2	1130	0	14.50	0.065
		6	14.10	0.095
		7	14.15	0.105
		8	14.45	0.200
		9	15.60	1.80
		10	15.80	3.05
17	1140	0	14.60	0.065
		5	14.60	0.065
		7	14.50	0.065
		8	14.50	0.065
		9	14.30	0.065
		10	14.30	0.100
		11	14.20	0.100
		11.5	15.30	0.130

16 July 1953

STA.	TIME	DEPTH m.	TEMP. °C.	Cl. °/oo
2	1100	0	20.60	0.185
		5	20.45	0.295
		7	20.40	0.495
		8	19.15	0.870
		9	19.85	1.40
		10	19.50	2.05
		11	18.40	3.40
		12	17.90	4.20
		13	16.80	6.85
	1150	0	20.85	0.180
		5	20.45	0.295
		7	20.30	0.470
		8	20.20	0.790
		9	19.85	1.20
		10	19.55	1.70
		11	19.10	2.15
4.6	1040	0	19.80	0.070
		5	19.55	0.075
		7	18.80	0.125
		8	18.30	0.220
		9	19.50	1.10
		10	18.45	2.50
	1215	0	19.85	0.070
		5	19.65	0.080
		7	18.40	0.180
		8	19.25	0.575
		9	19.10	1.25
		10	18.55	2.35
		10.5	18.50	2.45

STA.	TIME	DEPTH m.	TEMP. °C.	Cl. °/oo
5.2	1030	0	19.95	0.070
		5	19.65	0.070
		7	19.10	0.105
		8	18.40	0.370
		9	19.45	0.860
		10	18.80	2.00
		11	18.55	2.25
	1220	5	19.85	0.080
		7	18.25	0.155
		8	19.20	0.665
		9	18.95	1.00
		10	18.70	2.05
	1300	0	20.15	0.075
		5	19.65	0.080
		7	18.30	0.300
		8	19.15	0.835
		9	19.10	1.05
		10	18.65	2.10
	1310	5	19.75	0.085
		7	18.35	0.290
		8	18.80	0.590
		9	19.05	1.10
		10	18.70	2.10
	1320	0	20.30	0.070
		5	19.85	0.075
		7	19.05	0.125
		8	18.95	0.670
		9	19.10	1.00
		10	18.75	2.05

16 JULY 1953

STA.	TIME	DEPTH m.	TEMP. °C.	Cl. °/oo
5.2	1400	0	20.40	0.070
		5	19.75	0.075
		7	18.35	0.180
		8	18.20	0.710
		9	18.75	1.00
		10	18.65	2.15
	1535	6	18.75	0.105
		7	17.60	0.140
		9	17.55	0.780
		10	18.70	2.05
5.5	1025	0	20.05	0.070
		5	19.75	0.075
		7	18.75	0.130
		8	18.20	0.330
		9	19.20	1.05
	1230	5	19.95	0.070
		7	18.10	0.140
		8	18.55	0.575
		9	18.85	0.880
		9.5	18.65	1.20
5.7	1010	0	20.30	0.070
		5	19.80	0.075
		7	18.75	0.090
		8	17.10	0.275
		9	17.10	0.517
		10	16.85	1.05
		11	17.15	1.40
		12	13.25	2.60
		13	12.65	3.50
5.7	1235	5	19.70	0.070
		7	18.40	0.100
		8	16.90	0.280
		9	17.60	0.720
		10	17.10	1.00
		11	16.80	1.75
		12	14.20	2.80
		13	12.65	3.50
8.5	0950	0	20.50	0.080
		5	20.30	0.070
		6	19.90	0.075
		8	17.45	0.140
		9	16.30	0.220
		10	14.95	0.665
		11	14.10	1.25
		12	12.60	2.75
		13	12.05	5.50
		14	11.90	6.50

Department of Oceanography
University of Washington
Technical Report Distribution List

2 Geophysics Branch, (Code 416)
Office of Naval Research
Washington 25, D.C.

6 Director, Naval Research Laboratory
Attention: Technical Information Officer
Washington 25, D.C.

2 Officer-in-Charge
Office of Naval Research
London Branch Office
Navy #100, Fleet Post Office
New York, New York

1 Office of Naval Research Branch Office
346 Broadway
New York 13, New York

1 Office of Naval Research Branch Office
Tenth Floor, The John Crerar Library Building
86 East Randolph Street
Chicago, Illinois

1 Office of Naval Research Branch Office
1030 East Green Street
Pasadena 1, California

1 Office of Naval Research Branch Office
1000 Geary Street
San Francisco, California

1 Office of Technical Services
Department of Commerce
Washington 25, D.C.

5 Armed Services Technical Information Center
Documents Service Center
Knott Building
Dayton 2, Ohio

1 Assistant Secretary of Defense for Research & Development
Attention: Committee on Geophysics and Geography
Pentagon Building
Washington 25, D.C.

1 Office of Naval Research Resident Representative
University of Washington
Seattle 5, Washington

2 Assistant Naval Attache for Research
American Embassy
Navy #100, Fleet Post Office
New York, New York

2 Chief, Bureau of Ships
Navy Department
Washington 25, D.C.
Attention: (Code 847)

1 Commander, Naval Ordnance Laboratory
White Oak
Silver Spring 19, Maryland

1 Commanding General, Research and Development Division
Department of the Air Force
Washington 25, D.C.

1 Chief of Naval Research
Navy Department
Washington 25, D.C.
Attention: (Code 466)

8 U.S. Navy Hydrographic Office
Washington 25, D.C.
Attention: Division of Oceanography

2 Director, U.S. Navy Electronics Laboratory
San Diego 52, California
Attention: (Codes 550, 552)

1 Chief, Bureau of Yards and Docks
Navy Department
Washington 25, D.C.

1 Commanding General, Research and Development Division
Department of the Army
Washington 25, D.C.

1 Commanding Officer, Cambridge Field Station
230 Albany Street
Cambridge 39, Massachusetts
Attention: CRHSL

1 National Research Council
2101 Constitution Avenue
Washington 25, D.C.
Attention: Committee on Undersea Warfare

1 Project Arowa
U.S. Naval Air Station
Building R-48
Norfolk, Virginia

1 Department of Aerology
U.S. Naval Post Graduate School
Monterey, California

1 Chief of Naval Operations
Navy Department
Washington 25, D.C.
Attention: Op-533D

1 Commandant (OAO), U.S. Coast Guard
Washington 25, D.C.

1 Director, U.S. Coast & Geodetic Survey
Department of Commerce
Washington 25, D.C.

1 Department of Engineering
University of California
Berkeley, California

1 The Oceanographic Institute
Florida State University
Tallahassee, Florida

1 U.S. Fish & Wildlife Service
P.O. Box 3830
Honolulu, T. H.

1 U.S. Fish & Wildlife Service
Woods Hole, Massachusetts

2 Director, Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

1 Director, Chesapeake Bay Institute
Box 4264, RFD #2
Annapolis, Maryland

1 Director, Narragansett Marine Laboratory
Kingston, R. I.

1 Head, Department of Oceanography
University of Washington
Seattle, Washington

1 Bingham Oceanographic Foundation
Yale University
New Haven, Connecticut

1 Department of Conservation
Cornell University
Ithaca, New York
Attention: Dr. J. Ayers

1 Director, Lamont Geological Observatory
Torrey Cliff
Palisades, New York

2 Director, U.S. Fish & Wildlife Service
Department of the Interior
Washington 25, D.C.
Attention: Dr. L. A. Walford

1 U.S. Army Beach Erosion Board
5201 Little Falls Road N. W.
Washington 16, D.C.

1 Allen Hancock Foundation
University of Southern California
Los Angeles 7, California

1 U.S. Fish & Wildlife Service
Fort Crockett
Galveston, Texas

1 U.S. Fish & Wildlife Service
450 B Jordan Hall
Stanford University
Stanford, California

2 Director, Scripps Institution of Oceanography
La Jolla, California

1 Director, Hawaii Marine Laboratory
University of Hawaii
Honolulu, T. H.

1 Director, Marine Laboratory
University of Miami
Coral Gables, Florida

1 Head, Department of Oceanography
Texas A & M College
College Station, Texas

1 Head, Department of Oceanography
Brown University
Providence, Rhode Island

1 Department of Zoology
Rutgers University
New Brunswick, New Jersey
Attention: Dr. H. K. Haskins

1 Dr. Willard J. Pierson
New York University
New York, New York